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AFML-TR-70-58
Volume IV

ADVANCED COMPOSITES DATA FOR AIRCRAFT STRUCTURAL DESIGN

Volume IV: Material and Basic Allowable Development — Graphite/Epoxy

L.M. Lackman
D.O. Losee
J.A. Rohlen
T.T. Matoi

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SEP 1972

FOREWORD

This report was prepared by the Los Angeles Division of North American Rockwell Corporation under Contract F33615-68-C-1489 for the Advanced Composites Division, Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Mr. F. J. Fechek and Mr. R. L. Rapson (AFML/LC) were the Air Force Project Engineers for this effort, and Dr. L. M. Lackman was the North American Rockwell Program Manager.

The authors of Volume IV are Dr. L. M. Lackman, Mr. D. O. Losee, Mr. J. A. Rohlen, and Mr. T. T. Matoi. Mr. T. W. McGann and Mr. C. A. Moore supported the fabrication and testing efforts, respectively. The authors wish to acknowledge Mr. B. A. Burroughs' invaluable assistance in the area of data plots and specimen photographs. Mr. G. H. Arvin, as Editor in Chief, was responsible for the organization and continuity of this volume.

This report was submitted by the authors on 30 April 1972 for publication as a technical report.

This report has been reviewed and is approved.

Robert C. Tomashot
Robert C. Tomashot
Technical Area Manager
Advanced Composites Division

ABSTRACT

This volume is Volume IV of four volumes and summarizes that portion of the program under Contract F33615-68-C-1489 concerned with the material and basic allowable development of a specific current graphite-filament/epoxy-matrix advanced composite system. The specific system selected is known commercially as Type AS/3002 prepregged by Fiberite Corporation, with the fiber and matrix formulation supplied by Hercules Incorporated, the U.S. licensed distributor of Courtaulds fibers.

The main body of this volume comprises the following basic topics:

- Material qualification
- Specimen fabrication
- Specimen testing and data reduction
- Evaluation of results and generation of design allowables

The test program purpose is to characterize a singular graphite/epoxy system with the data divided into two categories: baseline data and environmental effects data. The purpose of the baseline data is to provide the basic materials, bonded and mechanical joint data, and fundamental configuration data at room, elevated, and subzero temperatures to support the design of graphite/epoxy airframe structural components. These data are augmented by the environmental effects data, which will establish the influence of the operating environment of high-performance aircraft on the design allowables of the graphite/epoxy system studies.

SPECIAL NOTE: Inasmuch as this is the final volume in this Technical Report, the errata for all previous volumes have been compiled in this volume as Appendix IV, the last appendix.

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LIST OF SYMBOLS

A	-	area, general (in.^{2})
$A_{ij(i,j=1,2,6)}$	-	extensional rigidities
A_n	-	net area of a test panel (in.^{2})
a	-	length dimension (in.)
b	-	width dimension (in.)
D_{ij}	-	flexural rigidities
D	-	diameter of hole or fastener (in.)
e	-	edge distance - centerline of hole to edge (in.)
E_L	-	Young's modulus of lamina parallel to filament direction (lb/in.^{2})
E_T	-	Young's modulus of lamina transverse to filament direction (lb/in.^{2})
E_x	-	Young's modulus of laminate in X direction (lb/in.^{2})
E_y	-	Young's modulus of laminate in Y direction (lb/in.^{2})
F	-	allowable stress, general (lb/in.^{2})
F_x, F_y	-	allowable axial stresses (lb/in.^{2})
F_{xy}	-	allowable inplane shear stress (lb/in.^{2})
f	-	applied stress, general (lb/in.^{2})
f_x, f_y	-	applied axial stresses (lb/in.^{2})
f_{xy}	-	applied inplane shear stress (lb/in.^{2})
G_{LT}	-	shear modulus of lamina in the LT plane (lb/in.^{2})
G'_{cx}	-	shear modulus of honeycomb sandwich core in the XZ plane (lb/in.^{2})

G'_{cy}	-	shear modulus of honeycomb sandwich core in the YZ plane (lb/in.^{2})
g	-	acceleration of gravity (32.174 ft/sec^2)
K_t	-	stress concentration factor
K	-	thermal conductivity (Btu-ft/ft^2 hr°F)
L	-	length (in.)
M	-	moment, general (in.-lb)
N	-	number of cycles in repeated loading
N_x, N_y, N_{xy}	-	distributed force components (lb/in.)
P	-	applied load (lb)
$Q_{ij(i,j = 1,2,6)}$	-	lamina elastic constants in laminate coordinate system
s	-	side distance - centerline of hole to side edge (in.)
T	-	temperature (°F)
t	-	(1) time (units depend on application; e.g., seconds, days, etc)
	-	(2) thickness (in.)
$T(t_f)$	-	final temperature, when measuring a temperature change
$T(t_o)$	-	original temperature, when measuring a temperature change
c	-	honeycomb core thickness (in.)
t_F	-	thickness of honeycomb sandwich face sheet (in.)
V	-	(1) shear force (lb)
	-	(2) volume (in.^{3})
W	-	width (in.)
α	-	coefficient of thermal expansion (in./in./°F)

α_L, α_T	-	lamina coefficient of thermal expansion in L and T directions (in./in./°F)
Δ	-	difference (used as a prefix to quantitative symbols)
θ	-	angular orientation of a lamina in a laminate; i.e., the angle between the L and X axes
ν_{LT}	-	Poisson's ratio relating contracting in the T direction due to extension in the L direction
ν_{TL}	-	Poisson's ratio relating contraction in the L direction due to extension in the T direction
ρ	-	density (lb/in.^{3})
ρ'_c	-	honeycomb sandwich core density (lb/ft^3)
σ	-	applied normal stress (lb/in.^{2})
ϵ	-	extensional strain (in./in.)
γ	-	shear strain (in./in.)

SUBSCRIPTS

a	-	adhesive
c	-	sandwich core
cr	-	critical value, in reference to instability failure
f	-	test failure value
L	-	longitudinal, in direction of L axis of lamina, parallel to filaments
pred	-	analytically predicted value
T	-	(1) transverse, in direction of T axis of lamina, inplane and perpendicular to filaments
	-	(2) value at temperature
test	-	value derived from test
ult	-	ultimate value at material failure

x,y,z	-	principal direction indicators in X,Y,Z coordinate system of laminate
xy, xz, yz	-	principal plane indicators in X,Y,Z coordinate system of laminate

SUPERSCRIPTS

cy	-	compression yield
tu	-	tension ultimate
cu	-	compression ultimate
isu	-	interlaminar shear ultimate
su	-	shear ultimate
t	-	tension
c	-	compression
s	-	shear

SECTION I

INTRODUCTION

The purpose of this program was to take the first step toward the generation and presentation of basic engineering data necessary to perform high-confidence-level structural design of primary aircraft structures utilizing advanced composite materials. The program was limited to an in-depth generation of basic material allowables for one boron/epoxy and one graphite/epoxy material system, and the determination of basic structural element response for the boron/epoxy system alone. The boron/epoxy portion of this program was conducted in conjunction with a concurrent General Dynamics/Fort Worth (GD/FW) program which was funded under Air Force Contract F33615-68-C-1474. The boron/epoxy system characterized by both these programs was Narmco 5505 (now available commercially as AVCO 5504/4) furnished by the supplier as 3-inch prepreg tape.

The boron portion of this program was conducted independently from the graphite/epoxy portion of the program and is described in detail in Volumes I, II, and III of this report. The graphite/epoxy portion of the program described in this volume consists of the characterization of an intermediate strength and modulus fiber/epoxy system which utilizes fibers obtained from the pyrolysis of the polyacrylonitrile (PAN) precursor. The specific system used was the commercially available Type AS fiber/3002 epoxy matrix prepreg from the Fiberite Corporation, utilizing Hercules Type AS graphite tows and Hercules formulated 3002 epoxy resin matrix. Additional data for these materials, as well as for other filament/matrix material systems, were obtained from published Government, industry, and technical journal reports, and were used to augment the data generated in this program.

This program was composed of three major work task areas:

Task I - Generation of Composite Material Design Allowables

Task II - Structural Element Test Program and Analysis Evaluation

Task III - Development of Advanced Composite Structural Design Manual for Aircraft

Task I was divided into two distinct areas of effort by the separate boron/epoxy and graphite/epoxy programs:

1. The purpose of the boron portion of task I was to complement the basic material design allowable activities conducted by GD/FW

and to develop acceptable laminate fabrication and inspection procedures. The boron effort was divided into the following work areas:

a. The establishment of program coordination procedures for the North American Rockwell Corporation and General Dynamics related programs

b. The accomplishment of a limited material development program

c. The generation of basic allowables for the constituent materials

d. Establishment of the accuracy of current analytical procedures for predicting certain basic allowables

e. The development, where reliable techniques were lacking, of prediction techniques for these basic material allowables

2. The graphite portion of task I consisted of the following:

a. The selection of the singular graphite/epoxy system to be characterized during the course of the program

b. The generation of baseline data to provide the basic material properties, bonded and mechanical joint data, and fundamental configuration data at room, elevated, and subzero temperatures to support the design of graphite/epoxy structural hardware

c. The generation of environmental effects data reflecting the influence of the operating environment of high-performance aircraft on the design allowables of graphite/epoxy materials.

The purpose of task II, which was concerned solely with boron/epoxy material, was to generate data on basic structural elements which form the building blocks from which aircraft structures are designed. A minimum evaluation of structural elements was conducted, including one basic laminate and one elevated temperature. Factors which were considered in the detail design of the structural elements included laminate orientations, panel proportions and edge restraints, effectiveness of typical forms of panel stabilization, evaluation of cutouts, and thermal gradient effects. One or more elements were selected for each primary and/or combined load application. The test program included local and general instability of flat panels and natural frequency determinations. The results of this test program were compared to predicted response, failure mode, and strength techniques for basic structural elements.

The task III work area was originally centered on the development of an advanced composite structural design manual for aircraft structures. The first effort of this task involved revision and refinement of the Aircraft Division of the Intermediate Draft of the Structural Design Guide developed by the Southwest Research Institute, San Antonio, Texas, under Air Force Contract AF33(615)-5142. The completely revised and reorganized Aircraft Division resulting from this phase of effort was published in the Final Draft of the Design Guide in November 1968 under Contract AF33(615)-68-C-1241. Soon thereafter, a review of the Final Draft by a select industry group led to a decision by AFML to reorganize the entire Design Guide for the First Edition, which was then assigned to NR/LAD under Contract F33615-69-C-1368.

Subsequent phases of task III of this program, in light of the foregoing developments, consisted of the preparation of the Aircraft System Applications chapter of the First Edition of the Design Guide as well as the preparation of data generated by tasks I and II of this program for incorporation into the various technical function-oriented chapters. Task III also included the incorporation into the Design Guide of data generated by the concurrent GD program.

The bulk of the basic material allowables for the 5505 material system was generated by the General Dynamics contract. This concurrent and integrally related contract was coordinated with the Los Angeles Division program effort through scheduled periodic coordination meetings. These meetings insured the continuous flow of pertinent program data between the two contractors.

This report is divided into four separate volumes, in each of which the subject areas of interest comprise an independent segment of the overall program. Each volume is a self-contained document, complementing the other three volumes but not dependent upon them for coherence or continuity. The titles of the four volumes are:

Volume I - Material and Basic Allowable Development - Boron/Epoxy

Volume II - Structural Element Behavior - Test and Analytical Determination

Volume III - Theoretical Methods

Volume IV - Material and Basic Allowable Development - Graphite/Epoxy

Laminate ply orientations are described and specified in this report by use of the laminate orientation code defined in the Advanced Composites Design Guide.

Volume IV contains the details concerned with the fabrication, testing, data reduction, evaluation, and generation of design allowables for the graphite/epoxy (Type AS/3002) system described.

Tables I and II present an overall description of the baseline data and environmental effects data test program, respectively. A preliminary evaluation program based on 7 pounds of Type A/3002 batch-untreated fiber was initially conducted as described in table III. The 36 bonded lap joint specimens and 30 mechanically fastened joints listed as "joints" in table III are considered as part of the baseline test program and are also listed in table I to provide a summary of the entire program. The "mechanical properties" specimens listed in table III for untreated Type A/3002 graphite/epoxy are also presented in this report as supplementary data.

Individual Design Guide standard data reporting forms are not presented in this volume. However, complete sets of these forms have been furnished to both the AFML Project Engineer and the Design Guide data bank.

TABLE I. GRAPHITE/EPOXY BASELINE DATA (TYPE AS/3002)

Data Area	Type of Load	Orientations Code	Orientations No.	No. Loading Directions	No. Geom	No. Temp	Replicates (70°F/350°F/-65°F)	Total Specimens	Test Configuration	Specimen Size (in.)	No. Plies	
Mechanical Properties Unidirectional	Tension	A	1	1**	1	3	(3/1/1)	5	Sandwich beam	1 x 22	6	
	Tension*	A	1	2	1	3	(4/5/5)	28	IITRI coupon	1 x 9	6	
	Compression*	A	1	1	1	3	(4/5/5)	14	Sandwich edge. compr	3 x 4	8	
	Compression*	A	1	1**	1	3	(6/5/5)	16	Sandwich beam	1 x 22	6	
	Shear-in plane*	A	1	1	1	3	(2/2/3)	7	Rail shear	4 x 8	6	
	Interlaminar shear	A	1	1	1	3	(5/5/5)	15	QC test	12 x 6	13	(1)
Crossply	Tension*	B C	2	1	1	3	(3/2/1)	12	IITRI coupon	1 x 9		
	Tension*	D E	2	2	1	3	(3/2/1)	34	IITRI coupon	1 x 9		
	Compression*	F	1	1	1	3	(3/2/1)	6	Sandwich edge. compr	3 x 4		
	Compression*	D E	2	1	1	3	(3/2/1)	12	Sandwich beam	1 x 22		
	Shear-in plane*	C D E	3	1	1	3	(3/3/1)	27	Rail shear	4 x 8		
	Interlaminar shear	C D E F G H	6	1	1	3	(3/2/1)	36	QC test	12 x 6		(1)
	Fatigue	A D E F	4	1	2 (2)	1	(5/0/0)	40	IITRI coupon	1 x 9		
Joints Bonded	Tension	D	1		3 (3)	2	(3/3/0)	18 [1]	Lap - composite to composite	1 x 9		
	Tension	E G	2	1	3 (3)	2	(3/3/0)	36	Lap - composite to composite	1 x 9		
	Tension	D	1	1	3 (3)	2	(3/3/0)	18 [1]	Lap - composite to metal	1 x 9		
	Tension	E G	2	1	3 (3)	2	(3/3/0)	36	Scarf - metal to composite	1 x 9		
	Compression	D E G	3	1	3 (3)	2	(1/1/0)	18	Lap - sandwich	3 x 6		
	Compression	D E G	3	1	3 (3)	2	(1/1/0)	18	Scarf - sandwich	3 x 6		
	Fatigue	D E G	3	1	1	2	(6/3/0)	27	Lap - coupon	1 x 9		
	Fatigue	D E G	3	1	1	2	(6/3/0)	27	Scarf - coupon	1 x 9		

(1) Total material required for all tests this line

(2) Two K_T's (no hole $K_T = 1$, Hole $K_T = 3$)

(3) Three geometries or three thicknesses

1 Type A/3002 - untreated fiber

* Ten percent of specimens were strain-gaged

**Run one RT specimen in transverse direction (T)

A [0]

B $[0_2/\pm45/90]$

C $[\pm45]$

D $[0/\pm45/90]$

E $[0/\pm45]$

F $[90/\pm45]$

G $[0_2/\pm45]$

H $[90_2/\pm45]$

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TABLE I. GRAPHITE/EPOXY BASELINE DATA (TYPE AS/3002) (CONCLUDED)

Data Area	Type of Load	Orientations Code	Orientations No.	No. Loading Directions	No. Geom	No. Temp	Replicates (70°F/350°F/-65°F)	Total Specimens	Test Configuration	Specimen Size (in.)
Joints Mechanical	Tension	D	1	1 ③④	6	3	(2/2/1)	30 [1]	Lap - coupon	1 x 9
	Tension	E G	2	1 ③④	6	3	(2/2/1)	60	Lap - coupon	1 x 9
	Compression	D E G	3	1 ③④	6	1	(1/0/0)	18	Lap - sandwich	3 x 6
	Fatigue	D E G	3	1 ④	2	1	(5/0/0)	30	Lap - coupon	1 x 9
Configuration Sandwich (3 core densities (3.1, 4.4, 5.7 pcf)	Tension	D E J	3	1 ⑤	3	2	(1/1/0)	18	Sandwich beam	1 x 22
	Compression	D E J	3	1 ⑤	3	2	(2/1/0)	27	Sandwich beam	1 x 22
	Compression	D E F	3	1 ⑥	3	2	(2/1/0)	27	Sandwich beam	1 x 22
Open Hole Tests	Tension	A I	2	1	1	2	(2/1/0)	6	IITRI coupon	2 x 9
	Tension	C G H D E F	6	1	1	2	(3/1/0)	24	IITRI coupon	2 x 9
	Compression	C D E	3	1	1	2	(3/1/0)	12	Sandwich beam	1 x 22
	Compression	A	1	1	1	2	(1/1/0)	2	Sandwich beam	1 x 22
Thickness Buildup Transverse Lands (3 buildups)	Tension	D E G	3	1	3	1	(3/0/0)	27	Coupon	2 x 9
							Total	721		

③ Three geometries or three thicknesses

④ Two-joint configuration (e.g., flush and protruding head)

⑤ Single-stage bonded

⑥ Secondary bonding

1 Type A/3002 untreated fiber

A	[0]	E	[0/±45]	H	[90_2/±45]
B	[0_2/±45/90]	F	[90/±45]	I	[0/90]
C	[±45]	G	[0_2/±45]	J	[0/±45] + Glass
D	[0/±45/90]				

TABLE II. ENVIRONMENTAL EFFECTS DATA (TYPE AS/3002)

Data Area	Type of Load	Orientations Code	Orientations No.	Environment No. Replicates	Environment No. Levels	Static Test Replicates 70°F/275°F/350°F	Total No. Type A Specimens	Test Configuration	Specimen Size (in.)
Thermal Cycling									
Unidirectional	QC	1	1	3 x 3 (1)	3 (5)	1/2/0	27	QC	12 x 12 (2)
Bonded Joints	Tension	2	1	3	3 (3)	3/0/0	9	Coupon	1 x 9
Mechanical Joints	Tension	2	1	3	3 (3)	1/2/0	9	Coupon	1 x 9
Nuclear									
Radiation	QC	1	1	3 x 3 (1)	3	3/0/0	27	QC	12 x 12 (2)
Thermal Pulse	Tension	4 2	2	1 (7)	1	1/1/0	4	IITRI coupon	1 x 9
	Compression	4 2	2	1 (7)	1	1/1/0	4	Sandwich	3 x 4
		4 2	2	1 (6)	1	1/1/0	4	Edge. comp	
Misc Environments									
Humidity	QC	1	1	3 x 3 (1)	3		27	QC	12 x 12 (2)
Salt Spray	QC	1	1	3 x 3 (1)	3		27	QC	12 x 12 (2)
Weathering	QC	1	1	3 x 2 (4)	2 x 2 (8)	3/3/0	24	QC	12 x 12 (2)
Fluids (2) Thicknesses	Permeability	1	1	3	1		6	Panel	4 x 4
Thermal Aging	QC	1	1	3 x 3 (1)	5 (5)	3/3/3	63	QC	12 x 12 (2)
Thermal-Physical Constants									
Coefficient of Thermal Expansion		3	6	3	1		18		
Thermal Conductivity (three thicknesses)		1	1	3	1		3		
Heat Capacitance (three thicknesses		1	1	3	1		3		
						Total	255		

1 [0]
2 [0/±45]
3 [0], [90], [0/±45], [90/±45], [0/±45/90], [90/±45/0]
4 [0/±45/90]
(1) QC tests - longitudinal flex, transverse flex, interlaminar shear.
(2) Total material required, this line
(3) Expose to cycling at RT to 270°F for 10 cycles, 100 cycles, 500 cycles, 3 each.
(4) Longitudinal flexure and interlaminar shear
(5) Controls at RT, 270°F, 350°F, 3 each. Test 3 at RT after 275°F for 500 hours, 3 at 270°F after 270°F for 500 hours. 3 at RT after 350°F for 500 hours, 3 at 350°F after 350°F for 500 hours.
(6) Test uncoated control speciman at RT and 270°F
(7) Coated specimen (5 mil HYSOL paint) thermal pulse 10 times with 22 percent static preload
(8) Coated and uncoated

TABLE III. FIBERITE GRAPHITE/EPOXY BATCH MATERIAL (TYPE A/3002) - INITIAL CHARACTERIZATION TESTS

Data Area	Type of Load	Lay-up Orientation	No. Loading Directions	No. of Temp	Replicates (70°F/350°F/ -65°F)	Total No.	Test Configuration	Specimen Size (in.)	No. Plies
Mechanical Properties									
Unidirectional	Tension	A	2	3	(2*/2*/2)	12	IITRI coupon	1 x 3	6
	Compression	A	1	3	(2*/0/0)	2	Sandwich - edge compr	3 x 4	6
	Shear-in-plane	A	1	3	(2*/2*/1)	5	Rail shear	4 x 8	6
	Interlaminar shear	A	1	3	(3/3/3) + 3 ①	12	QC test	0.25 x 0.60	13
	Flexure	A	1	3	(3/3/0)	6	QC test	0.50 x 4	13
	Compression	A	1	1	(1*/0/0)	1	Sandwich beam	1 x 22	6
Crossply	Tension	D	2	3	(3*/2*/1)	12	IITRI coupon	1 x 5	8
	Compression	D	1	3	(3*/3*/0)	6	Sandwich - edge. compr	3 x 4	8
	Shear-in-plane	D	1	3	(2*/2*/2)	6	Rail shear	4 x 8	8
Joints									
Bonded	Tension	D x 3**	1	2	(3/3/0)	18	Lap - composite to metal	1 x 9	8
	Tension	D x 3**	1	2	(3/3/0)	18	Lap - composite to composite	1 x 9	8
Mechanical	Tension	D x 3**	1	3	(2/2/1)		Lap - coupon	1 x 9	
						15	Flush		16
						15	Protruding		8
Thermal-Physical Constants Coefficient of Thermal Expansion		A	2		3	6			
					Total	134			

① 3 at 265°F

**Geometry variations

* Strain gage one specimen

A [0]

D [0/±45/90]

SECTION II

MATERIAL PROCUREMENT AND ACCEPTANCE

The graphite/epoxy fabrication technology utilized in this program was developed at NR/LAD under internally funded programs. This effort included the development of a material procurement specification (appendix I) and a preliminary process specification (appendix II).

MATERIAL SELECTION

Hercules 3002 resin and Type AS batch graphite fiber were selected for the graphite/epoxy advanced composite design data generation task. Initially, untreated Type A/3002 prepreg was procured from Fiberite Corp. and Ferro Corp. for comparative raw material evaluation.

Material qualification laminates, utilizing each supplier's prepreg, were fabricated together per NR/LAD Process Specification ST0105LA0013 (appendix II). The qualification laminates consisted of unidirectional 13-ply quality control, six-ply longitudinal and transverse IITRI type tension test specimens.

The Fiberite prepreg ("Patapar" paper backed) handling characteristics were excellent. However, laminate layup difficulty was encountered with the Ferro-supplied prepreg in removing the thin polyethylene backing film from very tacky prepreg and in layup handling. The Fiberite prepreg had fewer graphite fiber gaps and better visual uniformity than the Ferro-supplied prepreg.

Fiberite-supplied Type A/3002 batch prepreg had a cured laminate thickness of 5.9 to 6.1 mils per ply (ST0130LB0005 requirement is 6.0 ±0.4 mils per ply). The laminate bag side surface quality was excellent. The Ferro-supplied prepreg had a cured laminate thickness of approximately 4.0 mils per ply with a rougher bag side surface than the Fiberite laminate. The Ferro laminates were deleted from the program as a result of the comparative prepreg material handling and laminating characteristics. The quality control 13-ply flexure test data for the Fiberite-supplied material are shown in table IV.

The Type A/3002 laminate material demonstrated relatively low resin-critical strength and strain properties. In particular, the interlaminar shear stress and transverse tensile stress were approximately 10 Ksi and 2.7 Ksi at room temperature, respectively. These low strength properties could be expected to produce cross-ply laminates with poor transverse stress and strain capability and low interlaminar shear strength capability.

To improve these resin-critical properties, which are directly associated with the resin-fiber interface bond, 1-pound of Type AS treated continuous fiber preimpregnated with 3002 resin was obtained for testing. The surface-treated fibers produced both improved interlaminar shear and transverse tension strengths as shown in table V. Based on these data, AFML approved the procurement of treated Type A short fiber impregnated with 3002 resin for characterization, and NR Specification ST0130LB0005 material property requirements were modified. Refer to appendix I.

MATERIAL PROCUREMENT

Graphite/epoxy (Type AS/3002) 12- x 45-inch sheet prepreg was incrementally received from Fiberite Corp. Prepreg tape material was inspected visually, and measurements were made to determine conformance of both physical and mechanical properties to the requirements of NR Specification ST0130LB0005, type II, class 3, grade 1 (appendix I). This specification requires the physical and mechanical properties shown in table VI.

The prepreg material for this task was received in four lots. Each prepreg material lot received was qualified and requalified after the 90-day shelf life expiration. A 13-ply unidirectional laminate was laid up and cured for qualification purposes as follows:

- The laminate layup was held under vacuum pressure for 30 minutes prior to installation in the autoclave.
- The laminate was heated to 250°F in 30 minutes under vacuum pressure.
- After 30 minutes at 250°F, 100 psig autoclave pressure was applied (vacuum bag vented at 20 to 30 psig) in 10 minutes and the 250°F temperature maintained for a total time of 1 hour.
- The autoclave temperature was raised to 350°F and the laminate cured for 2 hours at 350°F under 100 psig pressure.
- The laminate was cooled at 150°F under full autoclave pressure and the laminate postcured at 350°F for 2 hours in a circulating air oven.

These quality control laminates were characterized by longitudinal flexure and short beam interlaminar shear test results shown in table VII.

TABLE IV. TYPE A (BATCH)/3002 13-PLY LAMINATE MECHANICAL PROPERTIES FOR FIBERITE LOT NO. 1A-65

Property	Test Temperature	Strength (Ksi)	
		Requirement*	Test
Longitudinal flexure	RT	170	257.5 255.6 245.4 252.8 avg
	350°F	120	199.5 202.1 184.9 195.5 avg
Short beam shear	RT	10.0	11.1 9.6 8.9 9.9 avg
	350°F	6.0	7.7 7.8 8.3 7.9 avg
Transverse tensile	RT	—	2.7 avg

*Specimens tested in accordance with NR Specification ST0130LB0005 (original issue)
Laminate per ply thickness 5.9 to 6.1 mils per ply (cured laminate thickness)

TABLE V. TYPE AS (CONTINUOUS)/3002 13-PLY LAMINATE MECHANICAL PROPERTIES FOR FIBERITE LOT NO. 1B5

Property	Test Temperature	Strength (Ksi)
Longitudinal flexure	RT	257.9 248.5 253.2 avg
	350°F	196.8 210.3 203.6 avg
Short beam shear	RT	15.3 17.8 16.5 avg
	350°F	10.6 10.4 10.5 avg
Transverse tensile	RT .	4.9 avg

TABLE VI. MECHANICAL AND PHYSICAL PROPERTY REQUIREMENTS OF ST0130LB0005, TYPE II, CLASS 3, GRADE 1

Mechanical Property Requirements*		
Test	RT	350° F
Longitudinal flexure (Ksi)	200.0	150.0
Short beam shear (Ksi)	13.0	8.0

*Based on 13-ply undirectional laminate with a thickness of 0.006 ±0.0004 inch per ply

Physical Property Requirements	
Resin solids, percent by weight	42 ±4
Volatile content, percent by weight	8 maximum
Tack	Shall adhere to itself when wrapped on a 2.0-inch mandrel
Gel time at 350°F, minutes	7 to 11
Drapability	Shall bend on a 1/16-inch radius mandrel with no evidence of tow damage

TABLE VII. TYPE AS/3002 BATCH QUALITY CONTROL TEST RESULTS

Mechanical Property	Test Temperature	Lot No. 1B-57A	1B-57B	1B-57C	1C-94	1B-57B1	1B-57C
		Quantity Received (pounds)					
		4.23	21.0	36.5	11.3	*	*
Longitudinal flexure (Ksi)	RT	222.9	213.3	223.1	230.0	250.4	193.9
		221.5	201.6	231.1	230.3	237.4	234.6
		239.2	243.2	195.7	256.4	269.2	215.8
avg		227.9	219.4	216.6	238.9	252.3	214.8
	350°F	200.9	183.4	186.3	196.8	214.7	211.2
		189.0	182.7	178.2	209.6	223.2	193.0
		189.1	179.7	190.4	210.4	202.9	209.4
avg		193.0	182.0	185.0	205.6	213.6	204.5
Short beam interlaminar shear (Ksi)	RT	18.37	17.88	17.50	16.20	17.60	17.07
		18.82	18.24	18.32	16.17	16.60	17.65
		18.40	18.30	18.13	16.08		
avg		18.53	18.14	17.98	16.15	17.10	17.36
	350°F	9.91	9.28	8.26	8.56	9.66	9.44
		9.87	9.09	8.92	8.78	9.56	9.74
		9.69	9.58	8.52	8.72	9.51	9.98
avg		9.82	9.32	8.57	8.69	9.58	9.72
Specimen thickness range (mils/ply)		5.9-6.1	6.4-6.6	5.8-6.2	5.7-6.0	5.6-6.1	5.5-6.0

*90-day requalification

FIBER VOLUME DETERMINATION

The graphite/epoxy fiber volume results of the Type AS/3002 batch material are as follows:

Material Lot No.	Laminate Orientation	Fiber Vol (%)		Average Fiber Vol (%)
		Method No. 1 Calc	Method No. 2 Calc	
1B-57	(0)	63.6	63.7	63.6
1B-57	(0)	59.1	59.7	59.4
1B-57	$(0/\pm45/90)_S$	58.7	58.2	58.4
1B-55	$(0)_{13}$	59.4	60.6	60.0

The standard nitric acid ingestion method for determining the fiber volume fraction could not be utilized in conjunction with the Type AS graphite fiber because of its attack on this fiber. The specific gravity of each of the composite specimens was determined, followed by the sulfuric acid-hydrogen peroxide experimental method of reference 9, which was performed by NR/Rocketdyne. From this analytical method, the weight percent of fiber was determined.

Noting that the "lots" of Type AS/3002 prepreg consist of several graphite fiber lots, the density of which is provided by the supplier, and the improbability of determining the fiber lot to which the cured specimens, correspond, several methods of determining fiber volume were utilized.

METHOD NO. 1 - CALCULATION FROM FIBER DENSITY

Employing the weight percentage of fiber and the cured composite specific gravity, a percentage fiber volume can be determined corresponding to several fiber lot densities using the equation:

$$V_f = \frac{W_f \, (S_p \, G_r)_c}{(S_p \, G_r)_f}$$

where

V_f = fiber volume (%)

W_f = weight percentage of graphite fibers (%)

$(S_p \, G_r)_c$ = specific gravity of cured composite

$(S_p \, G_r)_f$ = specific gravity of graphite fiber

METHOD NO. 2 - CALCULATION FROM CURED MATRIX (RESIN) DENSITY

Employing the weight percentage of fiber and the cured composite specific gravity, a percentage fiber volume, utilizing the density of the cured resin, as provided by the supplier, and assuming this volume remains constant for each shipment of prepreg, can be determined using the equation:

$$V_f = 100\% - \frac{[(100\% - W_f) \times (S_p \, G_r)_c]}{(S_p \, G_r)_r}$$

where

$(S_p \, G_r)_r$ = specific gravity of cured resin

Comparing these values to those obtained by method No. 1 usually displays correlation with one specific fiber lot density; this then is the value chosen to be typical of method No. 1.

SECTION III

SPECIMEN FABRICATION

SPECIMEN LAMINATE FABRICATION

The graphite/epoxy laminate requirements were established for the quantity of specimens by laminate orientation and thickness. The dimensional size of the laminates was standardized as much as possible and designed to take advantage of prepreg material sheet size and minimize the scrap factor. All specimen laminates for this task effort were fabricated in the Nonmetallics Materials and Process Engineering Laboratory.

The laminate layup and process procedures, in accordance with NR Specification ST0105LA0013, were consistently utilized in the fabrication of the test specimen laminates. The laminate fabrication procedures utilized are briefly described herein. The prepreg material, with the backing paper on both sides, was cut utilizing aluminum templates for the laminate plies. The material was laid up in a specific ply orientation sequence to produce the desired balanced laminate. Laminate plies consisting of two or more template cut pieces of prepreg were butt spliced. All laminate ply layup was black on black. A typical laminate layup and controlled resin flow bleeder system assembled for autoclave cure is shown in figure 1. All specimen laminates were cured and postcured in accordance with Specification ST0105LA0013.

Additional details of laminate fabrication are included in the following paragraphs for thickness buildup specimens and single-stage bonded-sandwich beam specimens.

CONVERSION OF LAMINATES TO SPECIMENS

The conversion of graphite/epoxy laminates into test specimens involved various machining and fabrication assembly operations, depending upon the desired specimen design configuration. All graphite/epoxy laminates were initially rough cut into smaller pieces utilizing a diamond slitting wheel with flood or spray mist water-soluble oil coolant. The fabrication procedures and materials utilized for the conversion of laminates into specimens are described herein.

Graphite/epoxy laminate test specimens, such as longitudinal (0°) flexure, short beam (interlaminar) shear, in-plane (rail) shear, and tension mechanical joint specimens, were machined utilizing a radial arm saw with a diamond slitting wheel and spray mist coolant. Test specimen drilling was accomplished

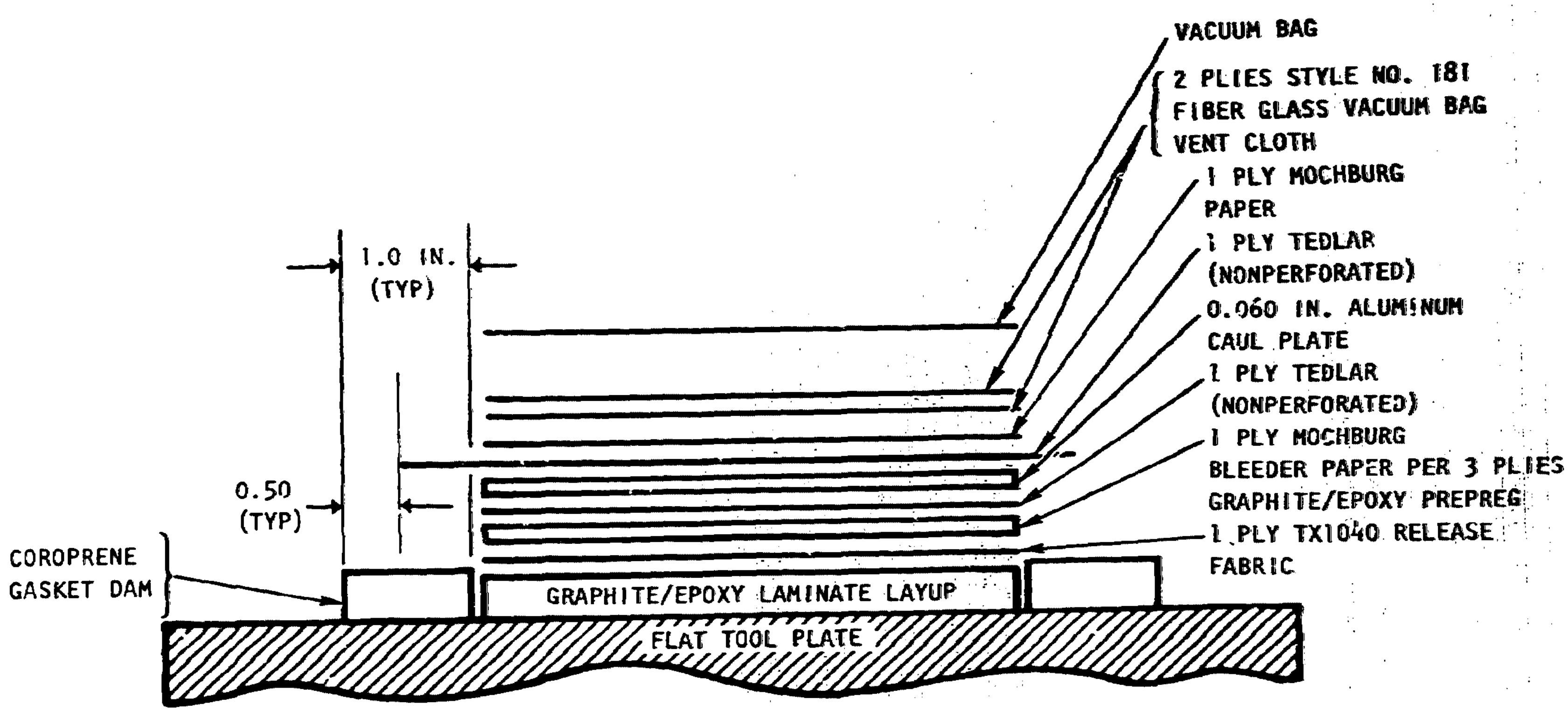


Figure 1. Typical Autoclave Cure Assembly for Graphite/Epoxy Laminate Fabrication

utilizing diamond core drills flooded with coolant. A drill jig was fabricated wherever possible for a test specimen type, such as in-plane (rail) shear, to reduce hole drilling costs and insure hole pattern coordination.

Many of the specimen types or configurations required common materials and/or processing to complete the test specimen fabrication. The test specimen fabrication operations utilized the materials and/or processes described as follows, except where otherwise stated:

1. All end tabs consisted of either four- or 11-ply 0°/90° press molded Scotchply laminate material, cured per manufacturer's instructions, with a 15° bevel machined onto one edge.

2. Graphite/epoxy and end tab laminate surface preparation for adhesive bonding involved lightly sanding bond surfaces followed by a solvent cleaning.

3. All syntactic foam details, consisting of epoxy resin and glass microballoons, were sanded to their required thickness and blasted with dry oil-free air to remove any loose particles prior to adhesive bonding.

4. Metlbond 329-7 adhesive was utilized and cured per manufacturer's instructions.

5. All bonding operations were conducted in an autoclave.

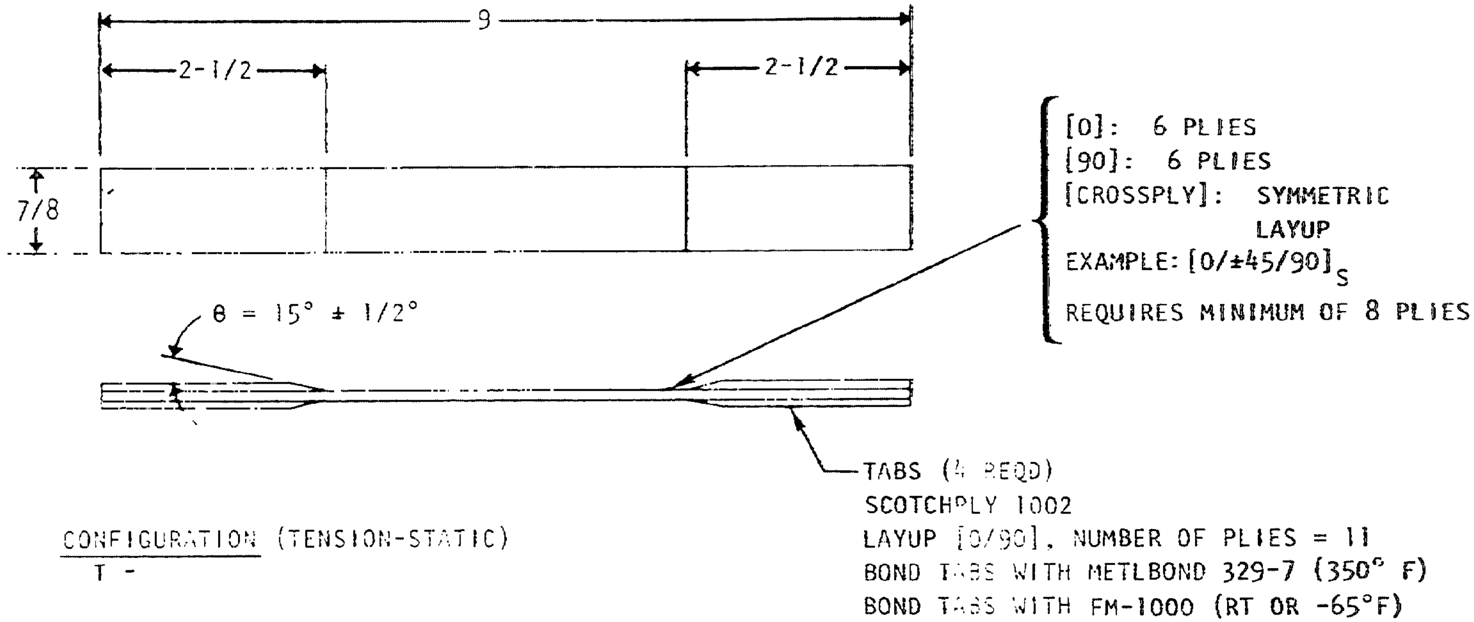
Specimen configuration drawings (figures 2 through 27) are shown with typical dimensional details, callouts, and identification codes for the baseline and environmental effects tests outlined in tables I and II.

TENSILE COUPON TYPE SPECIMENS

Some of the graphite/epoxy tensile specimens, such as Illinois Institute of Technology Research Institute (IITRI) coupons, open hole, and thickness buildup (figures 2, 3, and 4), require the use of end tabs which serve basically as load introduction mechanisms. Laminates for these types of specimens were of such a size as to produce multiple specimens per panel. End tabs were bonded onto these panels utilizing the FM-1000 (one ply of supported and one ply of unsupported) adhesive system for -65°F and room temperature test specimens, and the Metlbond 329-7 system for elevated temperature test specimens. These tabbed panels were then slit into their required widths. (See figure 2)

TENSION TEST (IITRI COUPON) 7/8 X 9

- STATIC TENSION



CONFIGURATION (TENSION-STATIC)

T -

- FATIGUE-TENSION

(CONFIGURATION SAME AS STATIC TENSION COUPON SHOWN ABOVE)

CONFIGURATION TYPE (TENSION-FATIGUE)

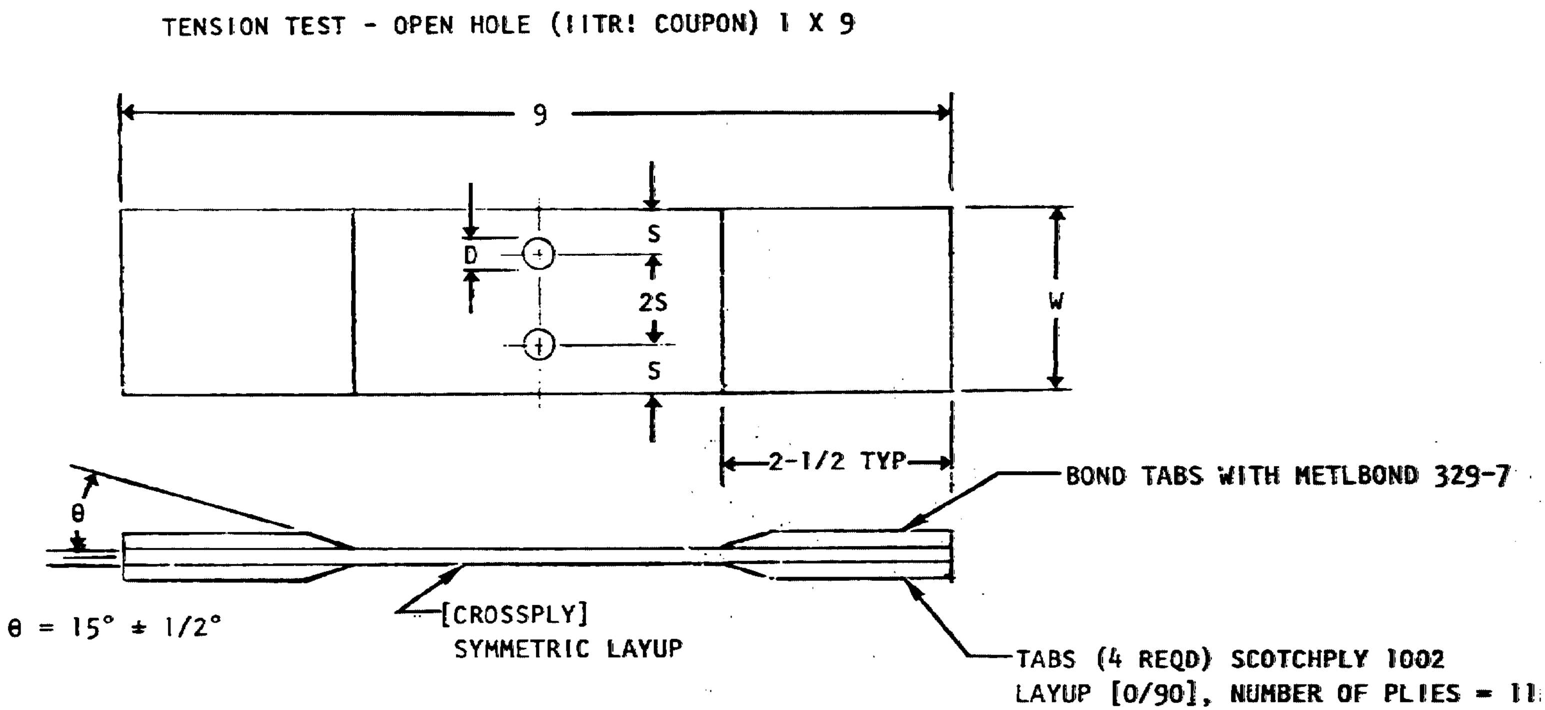
TF-

- ENVIRONMENTAL EFFECTS

CONFIGURATION TYPE (TENSION-THERMAL PULSE)

TTP-

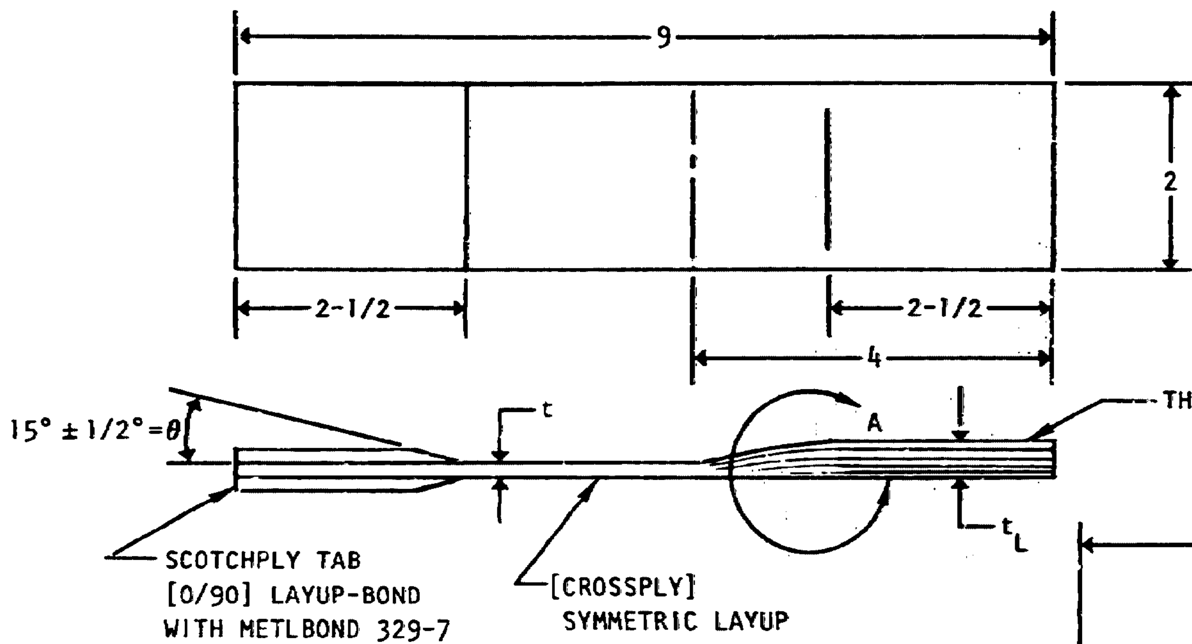
Figure 2. Tension Coupon - Test Specimen Configuration



CONFIG-URATION	D	S	W	D/2S
TOH	0.25	0.25	1.00	0.50

Figure 3. Tension - Open Hole Test Specimen

TENSION TEST - THICKNESS BUILDUP - TRANSVERSE LANDS (2 X 9)



CONFIGURATION TYPE (TENSION-THICKNESS BUILDUP)

	t_L
TTB-1.5T	1.5t
TTB-2T	2t
TTB-3T	3t

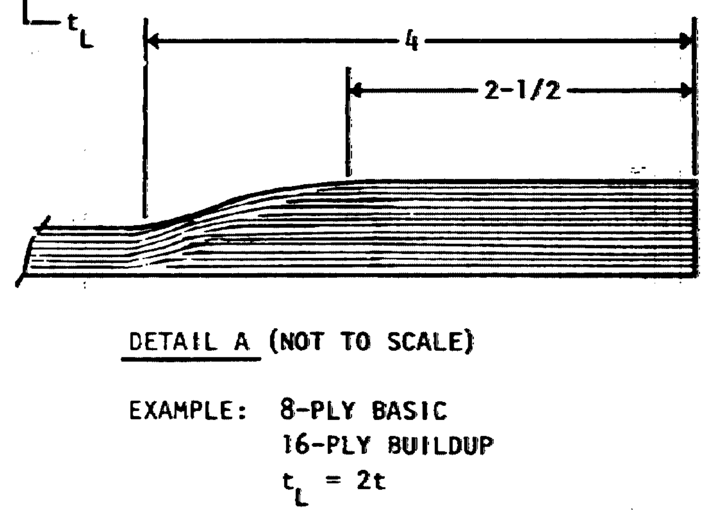


Figure 4. Thickness Buildup - Tension Specimen

Thickness Buildup Specimens

Figure 4 shows the dimensional details of the thickness buildup specimens. The thickness buildup configuration layup details are shown in figures 5, 6, and 7 for basic laminate orientations of $[0/\pm45/90]_S$, $[0/\pm45]_S$, and $[0_2/\pm45]_S$, respectively. Thickness buildups of 1.5, 2.0, and 3.0 times the basic laminate thickness were fabricated by interlayering additional plies oriented to provide laminate symmetry.

EDGEWISE COMPRESSION SPECIMENS

Standard short column sandwich edgewise compression specimens were fabricated basically to test the transverse laminate orientations. Multispecimen graphite/epoxy panels, together with their corresponding aluminum honeycomb core details (3/16-inch cell, 8.1 pounds per cubic foot, 1-inch thick) and adhesive, were assembled and cured. Both ends of these panels were then filled with a high-temperature epoxy potting compound, and machined flat and parallel to one another. Aluminum end tab strips (0.040-inch thick, 1-inch wide) with a 15° bevel machined onto one edge were press cured onto these panels. The panels were then slit into individual specimens (figure 8).

SANDWICH BEAMS

During this program, several types of tension and compression sandwich beam specimens were fabricated: secondary bonded beam specimens, both standard and open hole compression (figures 9 and 10), and single-stage and secondary bonded wrinkling beam specimens. Wrinkling or core variation beams (figure 12) differed from standard beams (figure 9) in that the latter consisted of a continuous piece of high-density (23 pounds per cubic foot) aluminum honeycomb core, whereas the former beam had a piece of low-density core spliced into the test section area between the higher density (23 pounds per cubic foot) core details. The sandwich beam load introduction point areas, which included the core splices on the wrinkling beams, were then potted with an aluminum-filled high-temperature epoxy compound. After these areas were cured, the loading pin holes were drilled.

Sandwich Beam - Secondary Bonded Facings

Secondary bonded sandwich beams, both standard and wrinkling, consisted of precured graphite/epoxy facings, slit from laminate panels, and 0.080-inch 17-7PH steel face sheets assembled onto the previously mentioned aluminum core substructure (bag side of graphite/epoxy facing to core) with the Metlbond 329-7 adhesive system.

ORIENTATION: THICKNESS BUILDUP CONFIGURATION

(a) $[0/\pm45/90]_S$

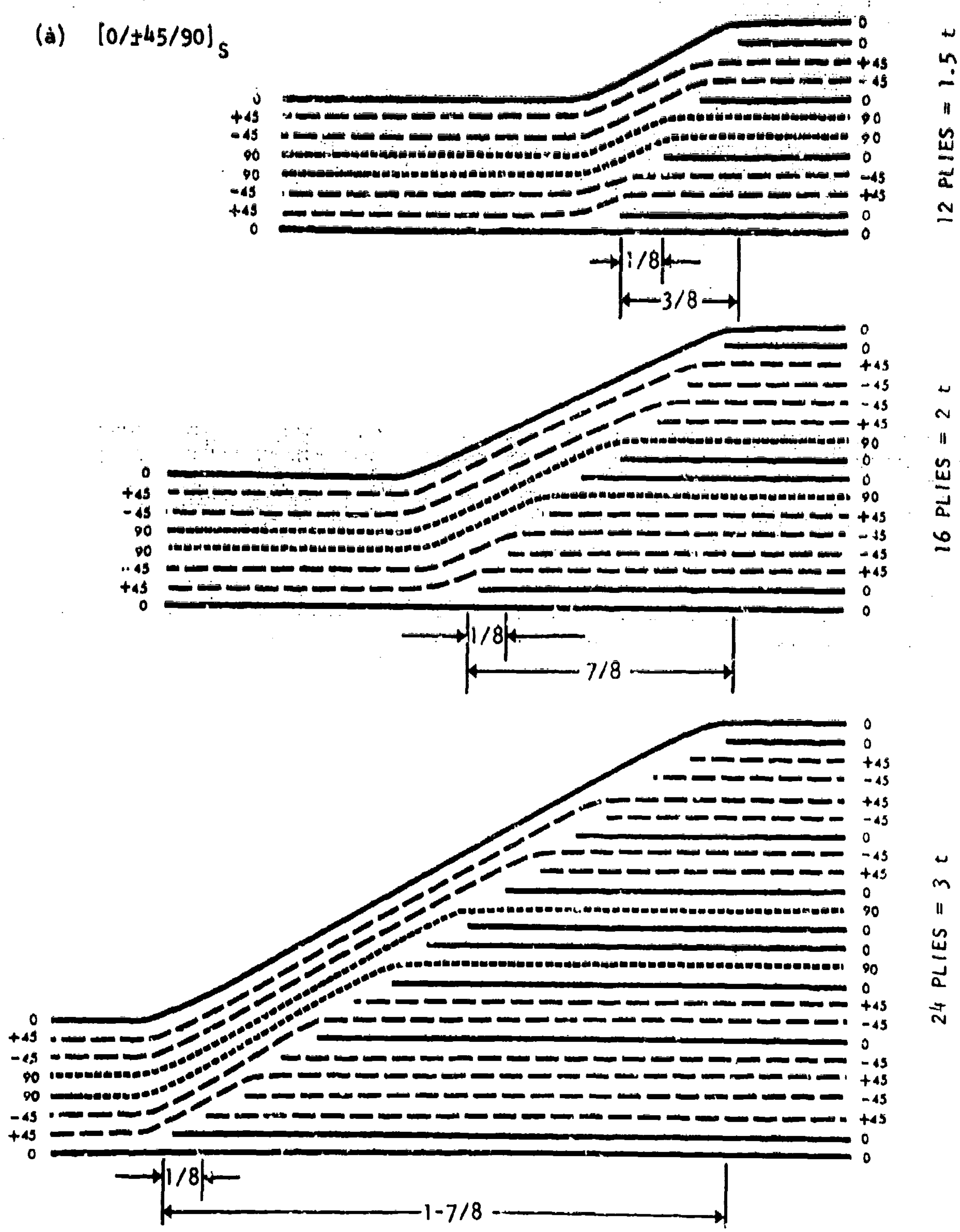


Figure 5. Graphite/Epoxy Thickness Buildup Details - $[0/\pm45/90]_S$ Basic Orientation

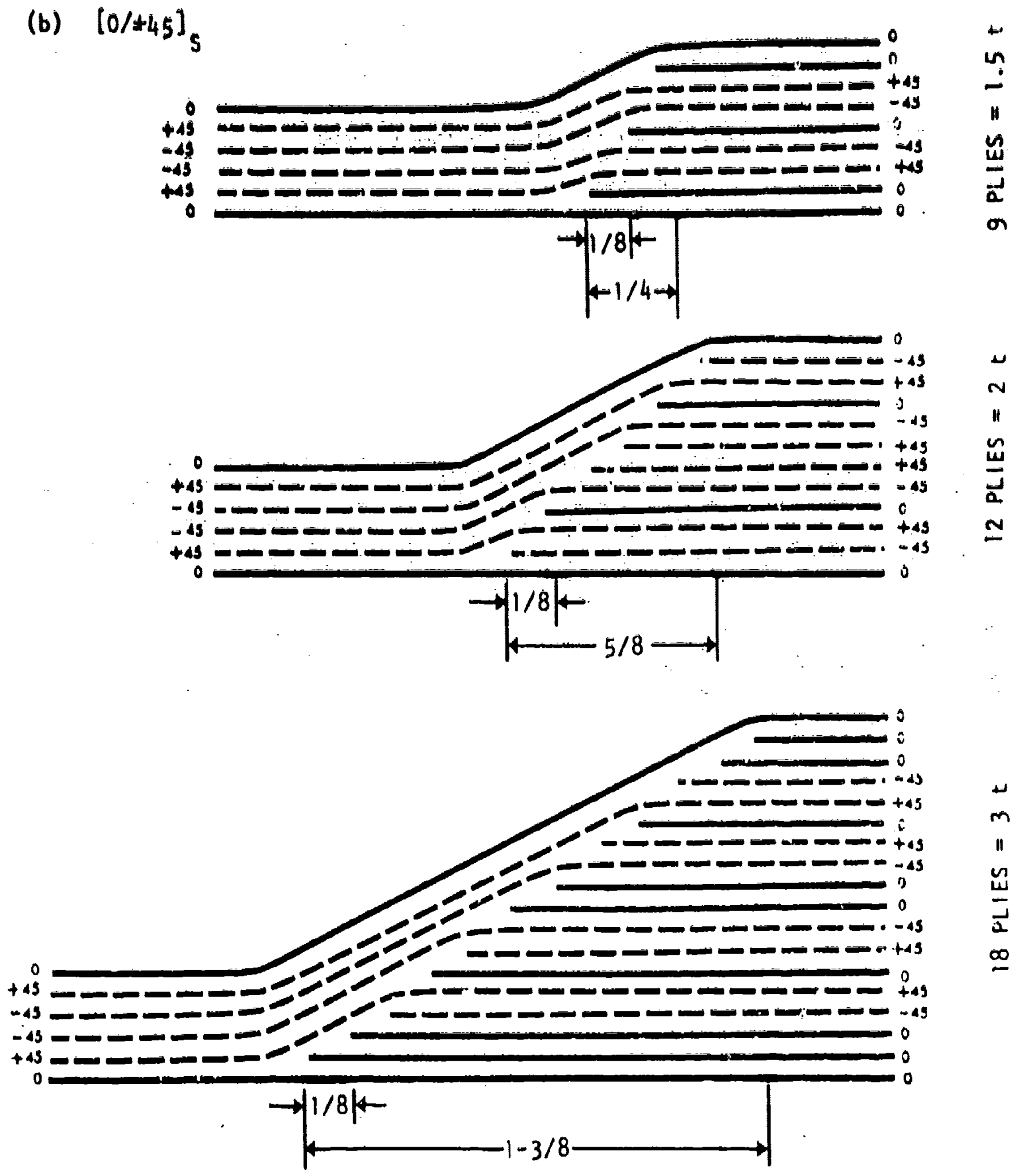


Figure 6. Graphite/Epoxy Thickness Buildup Details - $[0/\pm 45]_S$ Basic Orientation

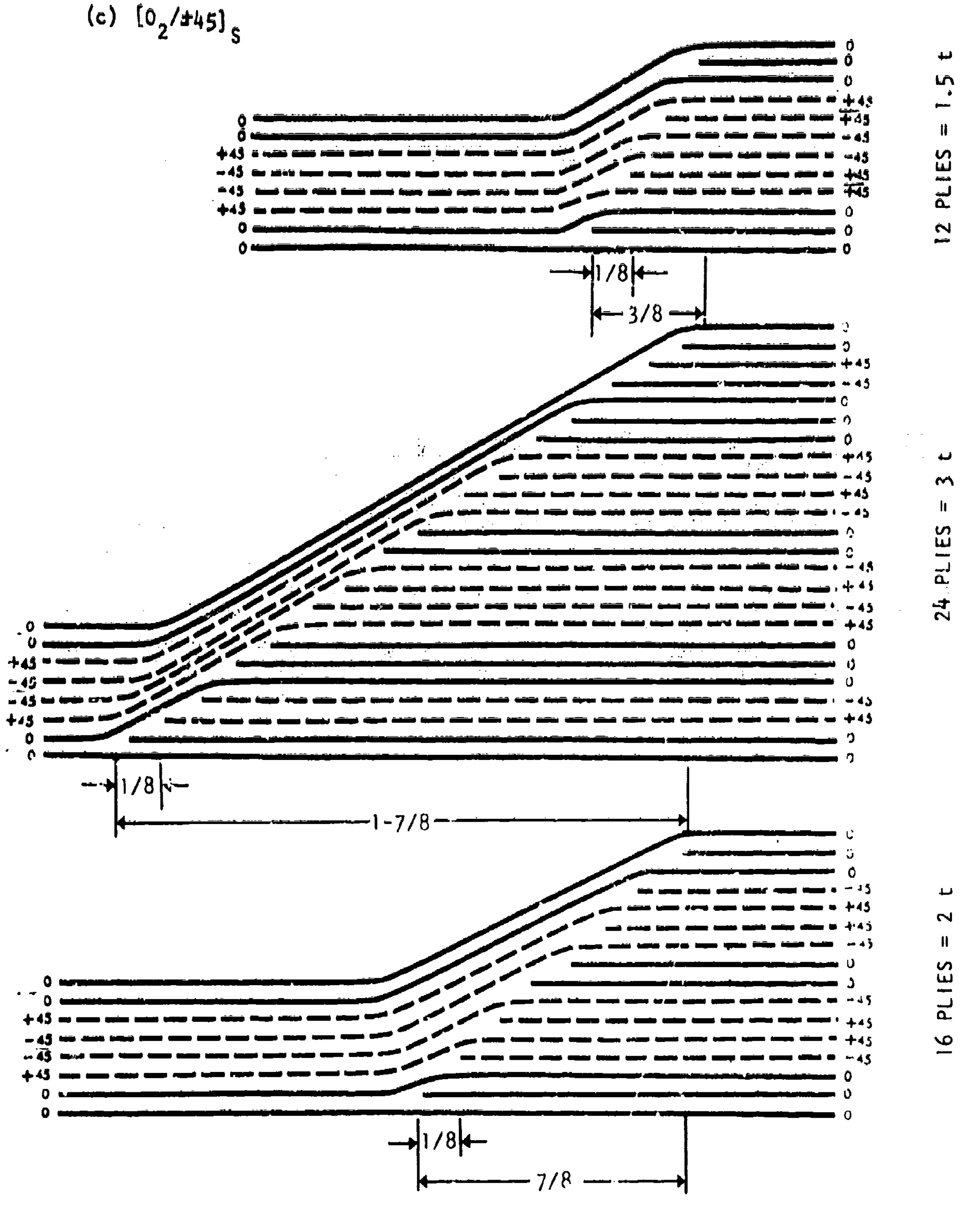
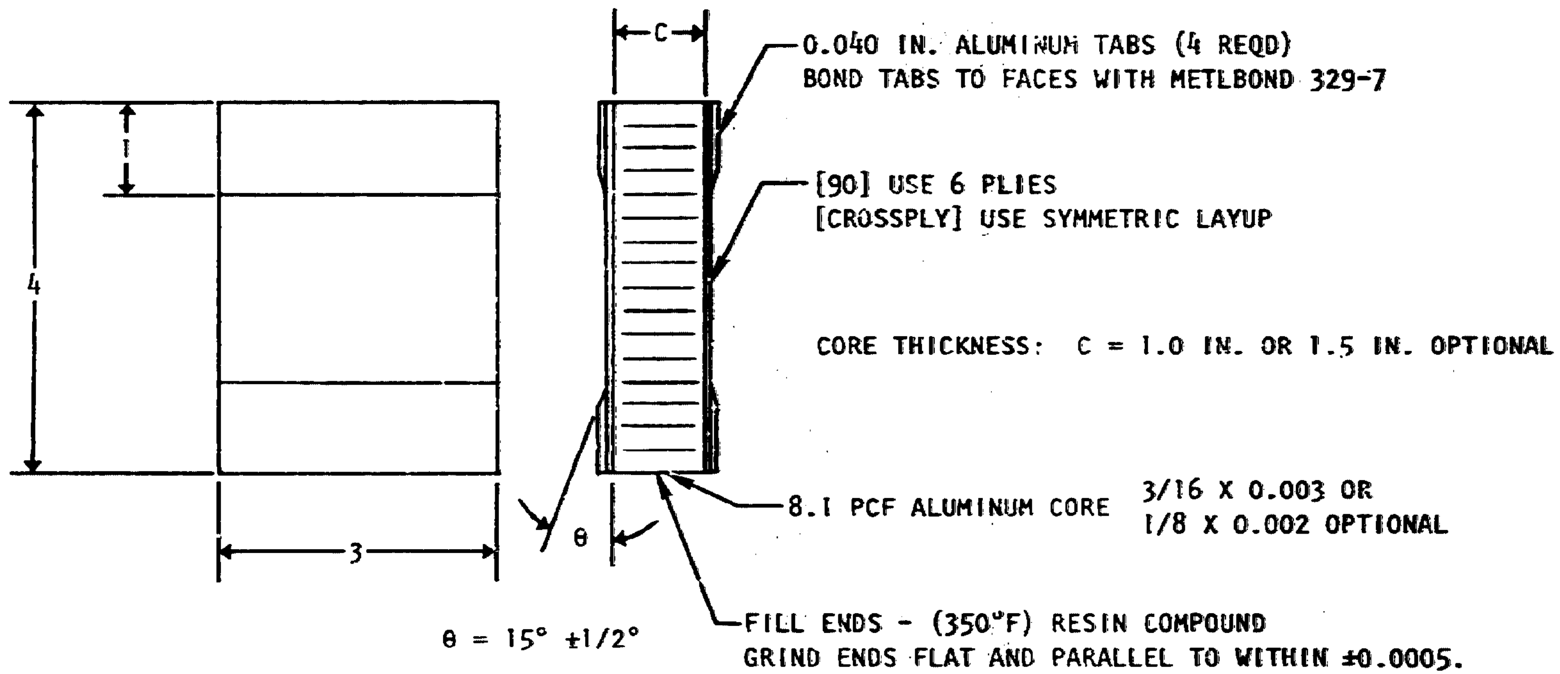


Figure 7. Graphite/Epoxy Thickness Buildup Details - $[0_2/\pm45]_S$ Basic Orientation

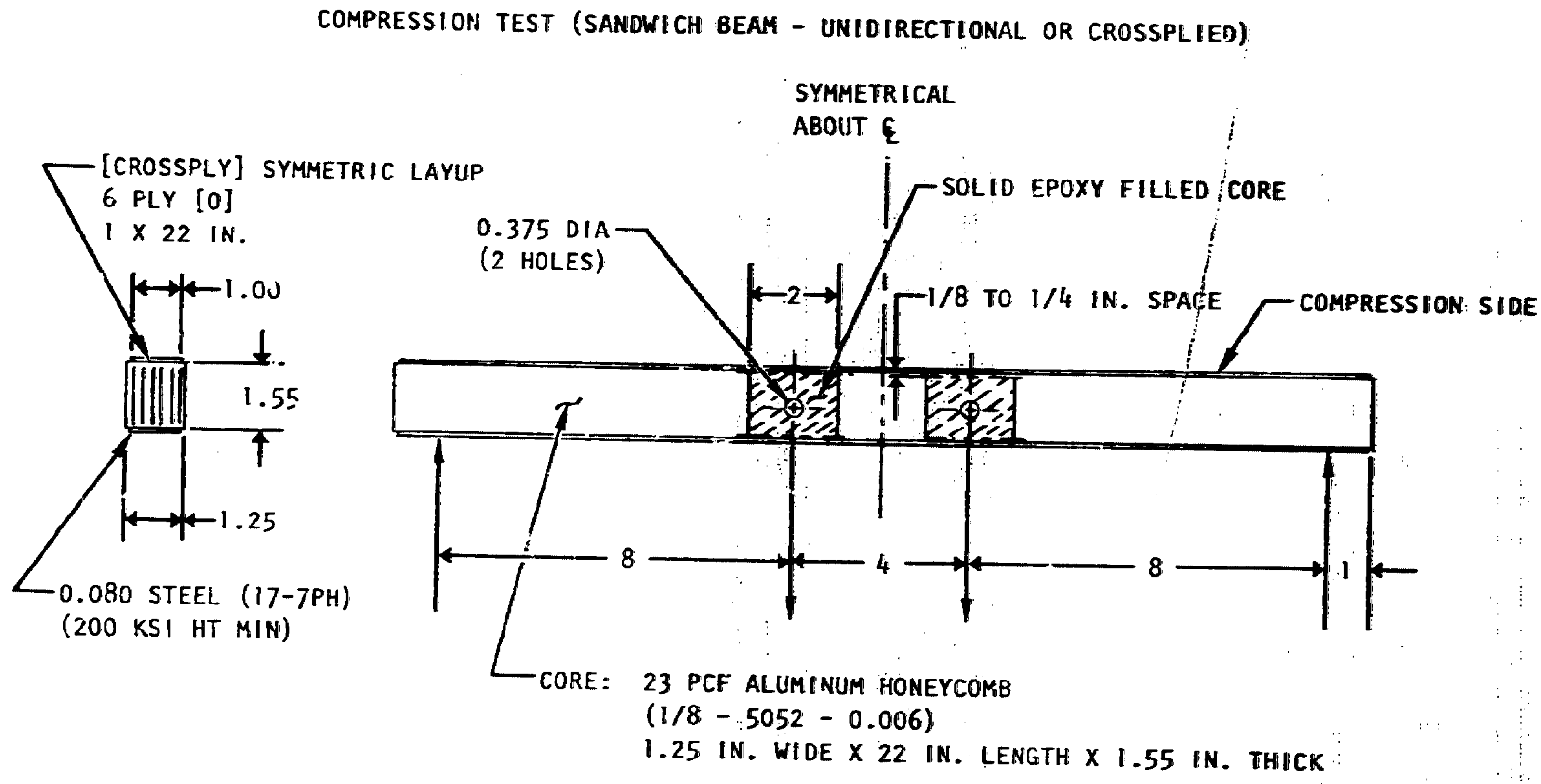
COMPRESSION TEST (SANDWICH-EDGEWISE COMPRESSION)



CONFIGURATION TYPE (EDGEWISE COMP.)

EC- (STATIC-COMPRESSION)
ECTP- (ENVIRONMENTAL - THERMAL PULSE)

Figure 8. Edgewise Compression - Sandwich Test Specimen



CONFIGURATION TYPE (COMPRESSION SANDWICH BEAM)

CLBB -

TENSION TEST (SANDWICH BEAM) SAME CONFIGURATION AS COMPRESSION BEAM LOADED IN INVERTED POSITION

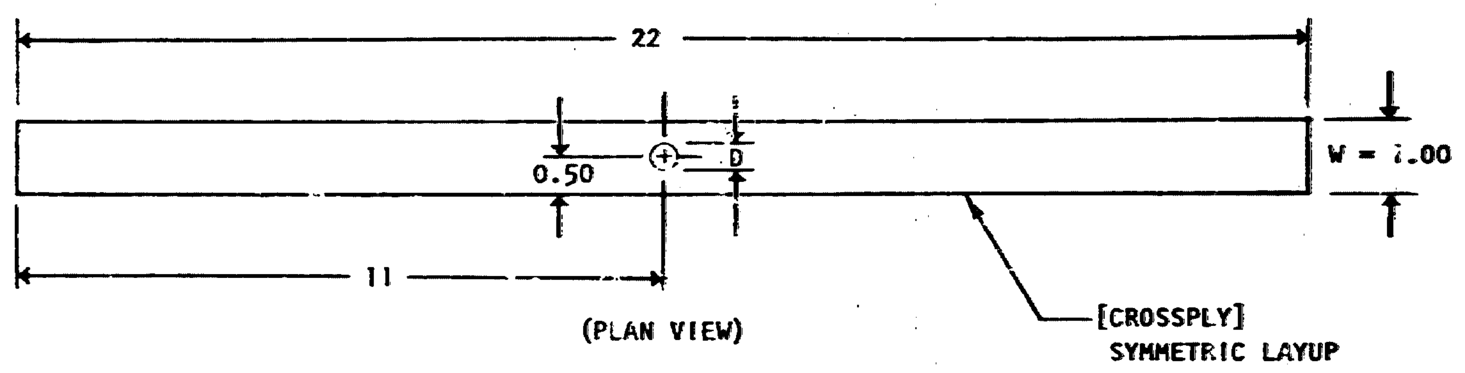
CONFIGURATION TYPE (TENSION SANDWICH BEAM)

TLBB -

Figure 9. Compression or Tension - Sandwich Beam Test Specimen

COMPRESSION - OPEN HOLE (SANDWICH BEAM) 1 X 1-1/2 X 22

SAME CONFIGURATION AS SANDWICH BEAM - UNIDIRECTIONAL (CLBB)
EXCEPT SINGLE HOLE IN LAMINATE AT MIDSPAN



CONFIGURATION TYPE	D	D/W
COH-	0.50	0.50

Figure 10. Compression - Open Hole - Sandwich Beam Specimen

In the case of the open hole compression specimens, holes were drilled in the graphite/epoxy face sheets prior to final assembly. The steel face sheets were grit blasted, using 220 grit, followed by an alkaline clean. The aluminum core was prepared for adhesive bonding by a light sanding in the filled area followed by an air blast and solvent spray with oven dry. These beams were press-cured.

Single-stage bonded wrinkling or core variation sandwich beams, instead of being individually fabricated as are secondary bonded beams, consisted of a multiple specimen sandwich construction. Additional details are given in the following paragraphs.

Sandwich Beam - Single-Stage Bonded Specimens

The fabrication of test specimens from precured laminates was accomplished with conventional support materials and processes. However, the fabrication of single-stage bonded tension and compression honeycomb sandwich beams involved nonstandard processing procedures. The layup sequence of materials is described herein and shown in figure 11. Figure 12 shows details of a typical sandwich beam test specimen.

Sequence of Operations

1. A 3.0-inch section of the proper lightweight core was spliced between two equal length sections of 23 pcf density core to form a 1-1/2 inch thick by 22-inch-long by width core subassembly.

2. The test loading lug zone (sandwich specimen) core subassembly was densified with aluminum filled/epoxy resin to include the core splice joint.

3. Tension and compression sandwich wrinkling flexure beams, identified TWS-6G or CWS-6G respectively, have a single-stage bonded epoxy/fiberglass laminate (one ply) bonded to the core subassembly with Metlbond 329-7 adhesive. (This operation is prior to cocuring operations.)

4. Adhesive-bonded surface preparation of the aluminum core, steel strips, and the fiberglass substrate laminate was in accordance with NR/LAD Specification ST0110LA0007.

5. The graphite prepreg laminate and cure preparation assembly were made by conventional techniques. (See figure 11.)

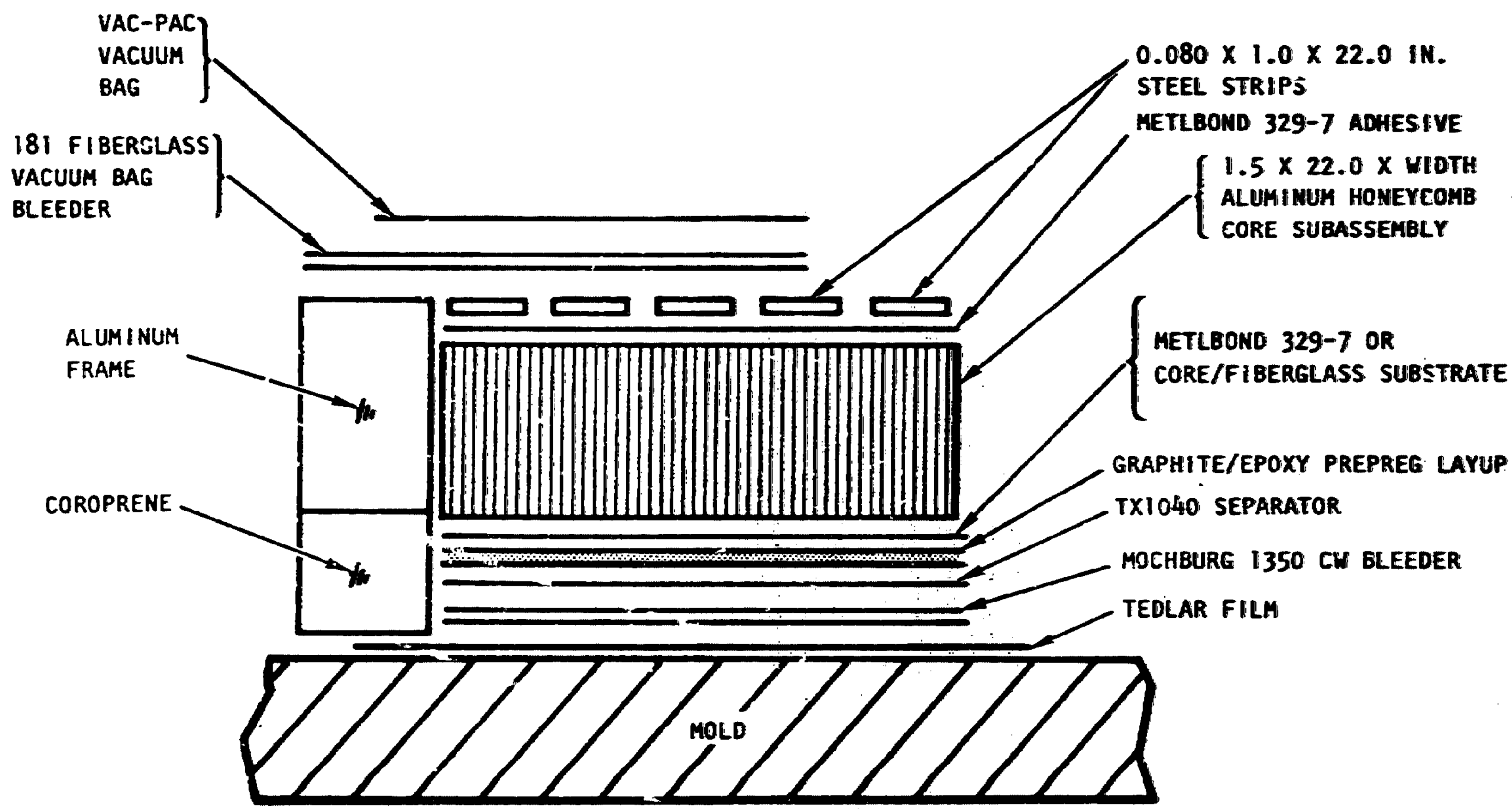
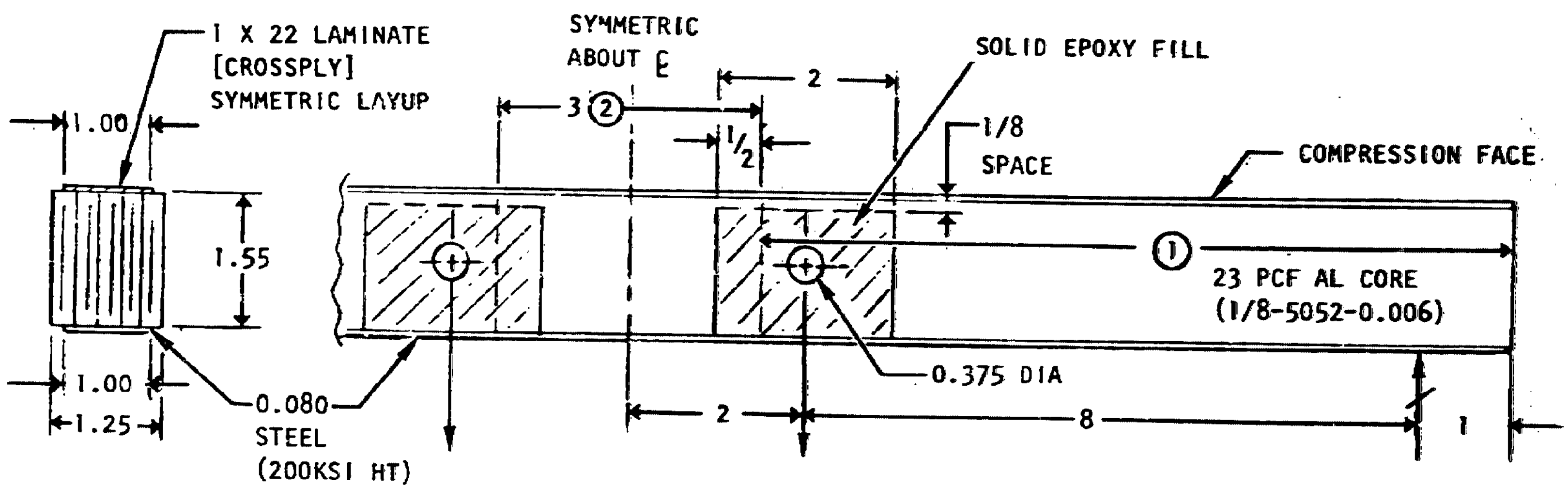


Figure 11. Single-Stage Bonded Graphite/Epoxy Laminate - Honeycomb Sandwich Panel Cure Assembly

COMPRESSION TEST (SANDWICH BEAM-WRINKLING) 1 X 1-1/2 X 22



CONFIGURATION		ALUMINUM CORE
1	2	
CWS-1	CW-1	2 = 3.1 PCF (3/16 -5056-0.001)
CWS-2	CW-2	2 = 4.4 PCF (3/16 -5056-0.0015)
CWS-3	CW-3	2 = 5.7 PCF (3/16 -5056-0.002)

CONFIGURATION 1 SINGLE-STAGE BONDING
CONFIGURATION 2 SECONDARY BONDING

TENSION TEST (SANDWICH BEAM - TENSION) 1 X 1-1/2 X 18

SAME AS COMPRESSION BEAM ABOVE EXCEPT LAMINATE LOCATED ON TENSION FACE (INVERT BEAM IN FIXTURE) WITH CONFIGURATION 1 SINGLE-STAGE BONDING.

CONFIGURATION

TWS-1, 3.1 PCF
TWS-2, 4.4 PCF
TWS-3, 5.7 PCF

Figure 12. Sandwich Beam Specimen - Compression Wrinkling or Tension

6. The sandwich assembly and graphite laminate were cured in accordance with the graphite laminate cure cycle previously reported, except that the 2-hour, 350°F postcure was added to the normal 1-hour, 350°F, 100 psig autoclave cure time.

7. Wrinkling sandwich beam specimens were machined from honeycomb sandwich panel in two steps:

   a. Graphite laminate slitting with a diamond wheel

   b. Aluminum core with a bandsaw

8. The loading lug holes were drilled at the neutral axis of each beam on 4.00-inch centers in the middle of the densified core zones.

RAIL SHEAR SPECIMEN (IN-PLANE SHEAR)

Figure 13 shows the typical dimensional details of the rail shear specimen which utilized the conventional laminate layup and machining techniques described previously.

QUALITY CONTROL TYPE SPECIMENS

Interlaminar Shear

Standard quality control type specimens, as shown in figure 14, were fabricated. These were tested to yield interlaminar shear values. Although the crossplied laminate specimens had span/thickness ratios ($^S/t$) not exactly equal to the unidirectional (13-ply) standard ($^S/t$ = 5.13), they ranged from 4.17 to 5.56 and were deemed to yield comparable values.

Longitudinal Flexure Specimen

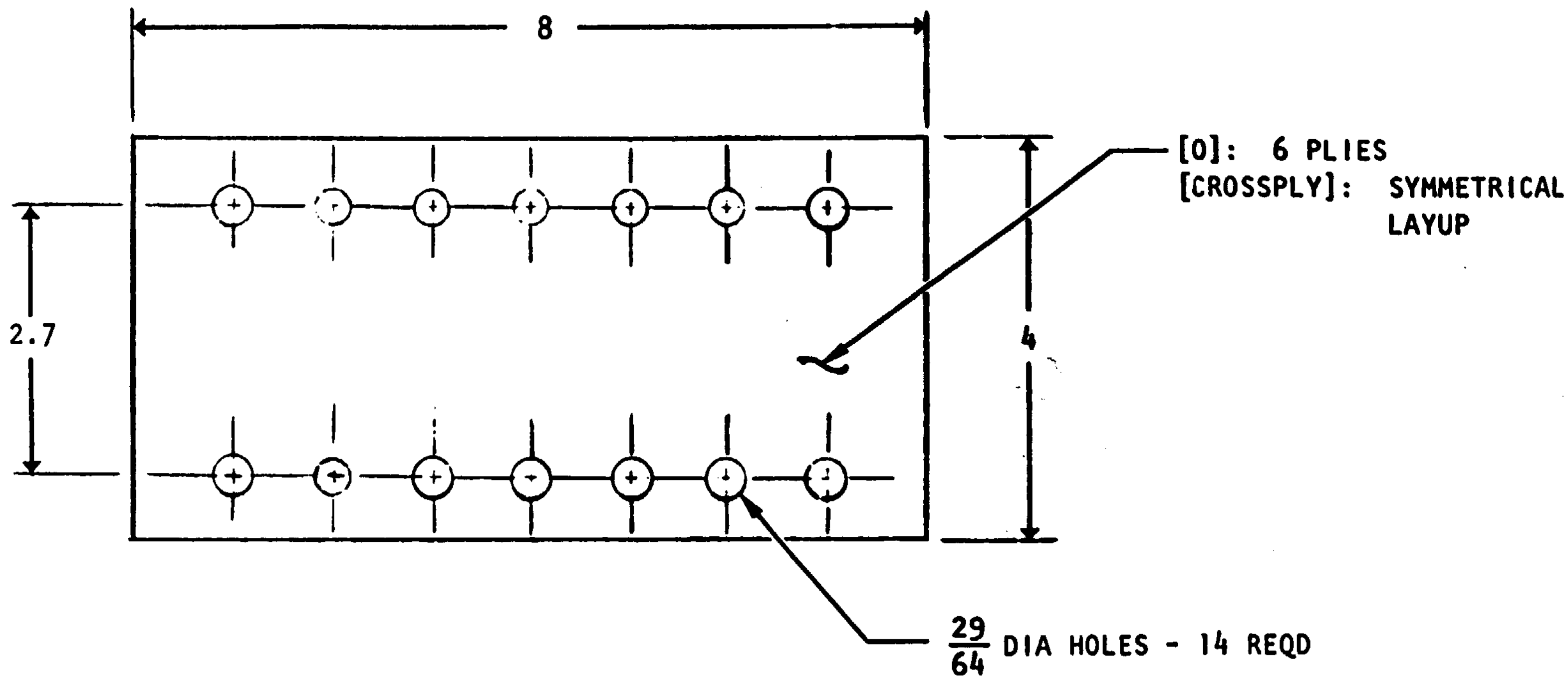
Standard quality control type specimens, as shown in figure 15, were fabricated to be used in the "environmental effects" portion of the test program.

BONDED JOINTS

Bonded Lap Joint Specimens

Composite-to-composite bonded joint lap shear specimens, tension (static and fatigue) and short column lap joint sandwich compression, were constructed utilizing multiple specimen laminate panels previously cut in such a way as to

SHEAR IN-PLANE TEST (RAIL SHEAR) 4 X 8



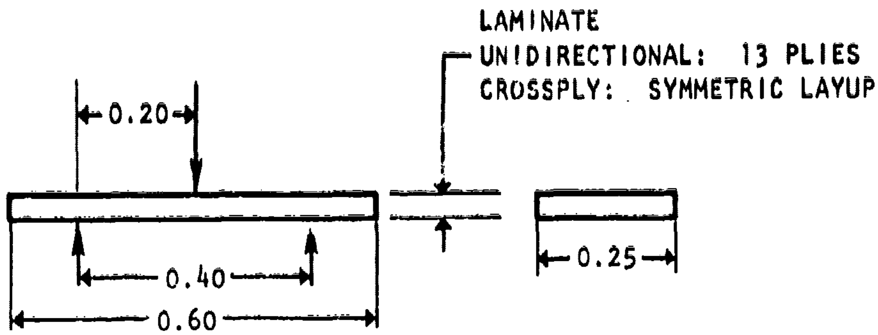
NOTE:

1. MATCH DRILL SPECIMEN WITH RAIL SHEAR JIG FIXTURE LOCATED IN STRUCTURES LABORATORY
2. USE CLIP-ON END SUPPORT AND REACTION PLATES AT FREE EDGES.

<u>CONFIGURATION TYPE</u> (RAIL SHEAR)
RS-

Figure 13. Rail Shear Test Specimen

INTERLAMINAR SHEAR

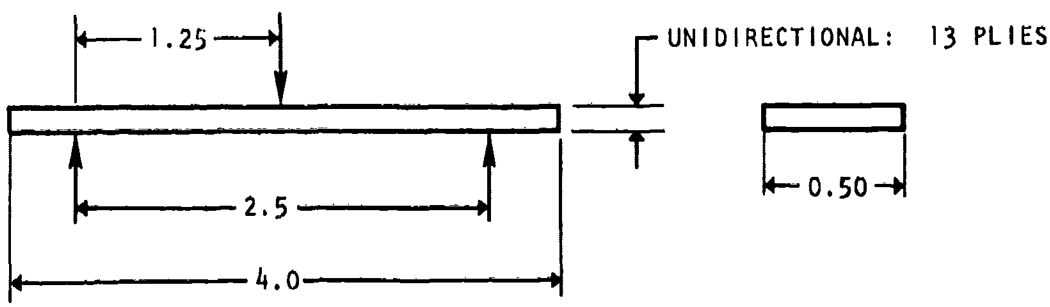


CONFIGURATION TYPE:

HS - (UNIDIRECTIONAL - 13 PLY)
ILS - (CROSSPLIED - SYMMETRIC LAYUP)

Figure 14. Interlaminar Shear - Short Beam Test Specimen

LONGITUDINAL FLEXURE



UNIDIRECTIONAL - 13 PLY

Figure 15. Longitudinal Flexure Specimen

produce matched specimen alignment when bonded bag to bag surface. Strips of end tab laminate material were bonded onto these graphite/epoxy panels during the lap joint configuration curing operation. Tension laminate panels were then further cut into individual specimens (figure 16).

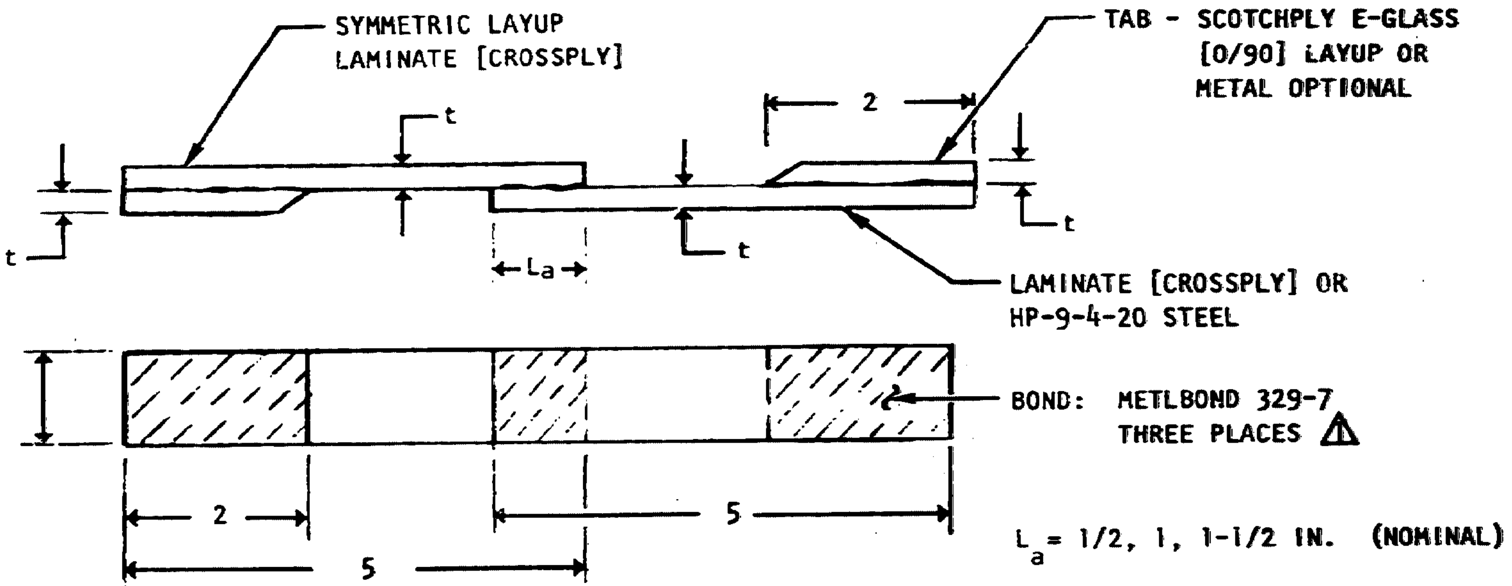
Compression laminate facings were then assembled onto a combination of syntactic foam and aluminum honeycomb core (3/16-inch cell, 8.1 pounds per cubic foot, 1-inch-thick). Several plies of adhesive were applied to all bonding surfaces (including the foam to core interface) to insure proper facing fitup. After cure, the edge of this sandwich assembly, containing the honeycomb core, was filled with a high-temperature potting compound and both ends were ground flat and parallel to one another. These panels were then slit into individual short column sandwich compression specimens. (See figures 17, 18, and 19.)

The composite to HP-9-4-20 steel lap shear bond joint specimens were assembled individually (the graphite/epoxy adherends being cut from a larger panel) and the joint configuration and end tab assembly were bonded simultaneously. (See figure 16.) Both the steel adherends and the end tabs were cleaned by grit blasting, using 220 grit, followed by an alkaline clean.

Bonded Scarf Joint Specimens

Graphite/epoxy - titanium double scarf bonded joint specimens, both tension (static and fatigue) and compression scarf joints, involved extensive machining and subassembly operations. All scarf-taper configurations were machined into the titanium adherends, but because of milling limitations only the 0.4-inch taper length could be machined into the corresponding graphite/epoxy laminate panels, utilizing a milling apparatus. The two other composite joint taper lengths were produced by hand sanding the laminate panels to match their respective titanium counterparts. The graphite/epoxy laminate adherend panels, bag surface to bag surface, were assembled with their matching titanium panels; the titanium was cleaned prior to adhesive bonding by vapor honing followed by an alkaline clean and a Pasa-Jell 107 paste etch. Additional plies of adhesive were applied in nonjoint areas to accommodate fitup problems, and this entire subassembly was cured on a flat plate. These panels were then slit into individual 1-inch-wide tensile coupons and/or matched sandwich facings. Glass/epoxy end tabs were bonded onto the composite ends of the tension specimens. (See Figures 20 and 21.) The compression scarf joint sandwich facings were sanded and the composite surfaces solvent cleaned, while the titanium adherend surfaces were re-etched with Pasa-Jell 107 paste. Matched sandwich facings were then assembled onto aluminum honeycomb details (3/16-inch cell, 8.1 pounds per cubic foot, 1-inch-thick) and bonded simultaneously with 1.0-inch-wide strips of laminate end tab material. The ends of these sandwich panels were filled with a high-temperature epoxy potting compound, and machined flat and parallel to one another. These sandwich assemblies were then cut into individual specimens. (See figures 22 and 23.)

BONDED JOINT (TENSION-SINGLE LAP SHEAR-COUPON)
COMPOSITE TO COMPOSITE
COMPOSITE TO METAL



NOTE: CONFIGURATION FOR STATIC AND FATIGUE TESTING WILL BE THE SAME.

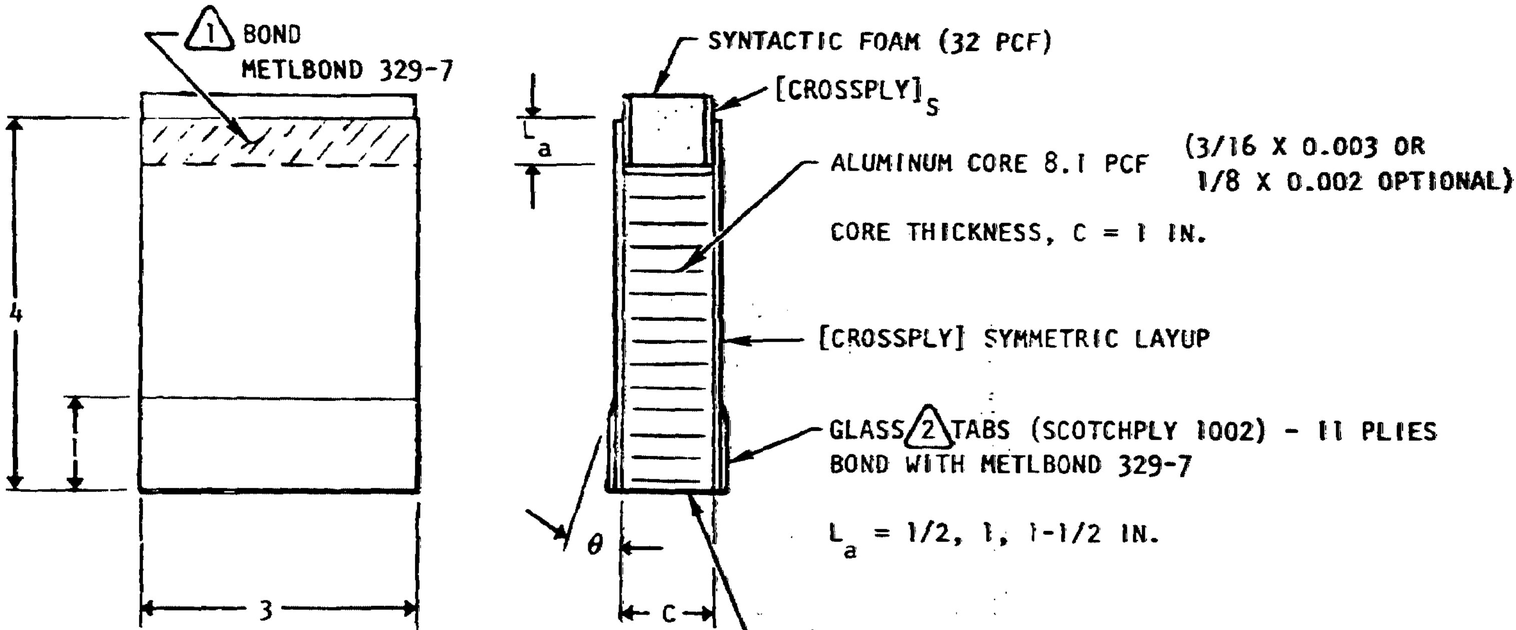
CONFIGURATION TYPE:

BGG-(STATIC) (BONDED GRAPHITE-GRAPHITE)
BGGF-(FATIGUE) (BONDED GRAPHITE-GRAPHITE)
BGM-(STATIC) (BONDED GRAPHITE-METAL)
BGGTC-(ENVIRONMENTAL EFFECT-PRIOR THERMAL CYCLING EXPOSURE)

⚠ ROUGHEN FAYING SURFACE AND SOLVENT CLEAN PRIOR TO BONDING.

Figure 16. Bonded Joint - Single Lap - Tension Specimen

BONDED JOINT (COMPRESSION - LAP SHEAR - SANDWICH) COMPOSITE TO COMPOSITE



$\theta = 15° \pm 1/2°$

2 NOTE: FINAL CONFIGURATION TABS ON BOTH ENDS (4 REQD)

CONFIGURATION TYPE (COMPRESSION - LAP SHEAR - SANDWICH)

1 ROUGHEN FAYING SURFACE AND SOLVENT CLEAN PRIOR TO BONDING

Figure 17. Bonded Joint - Lap - Compression Specimen

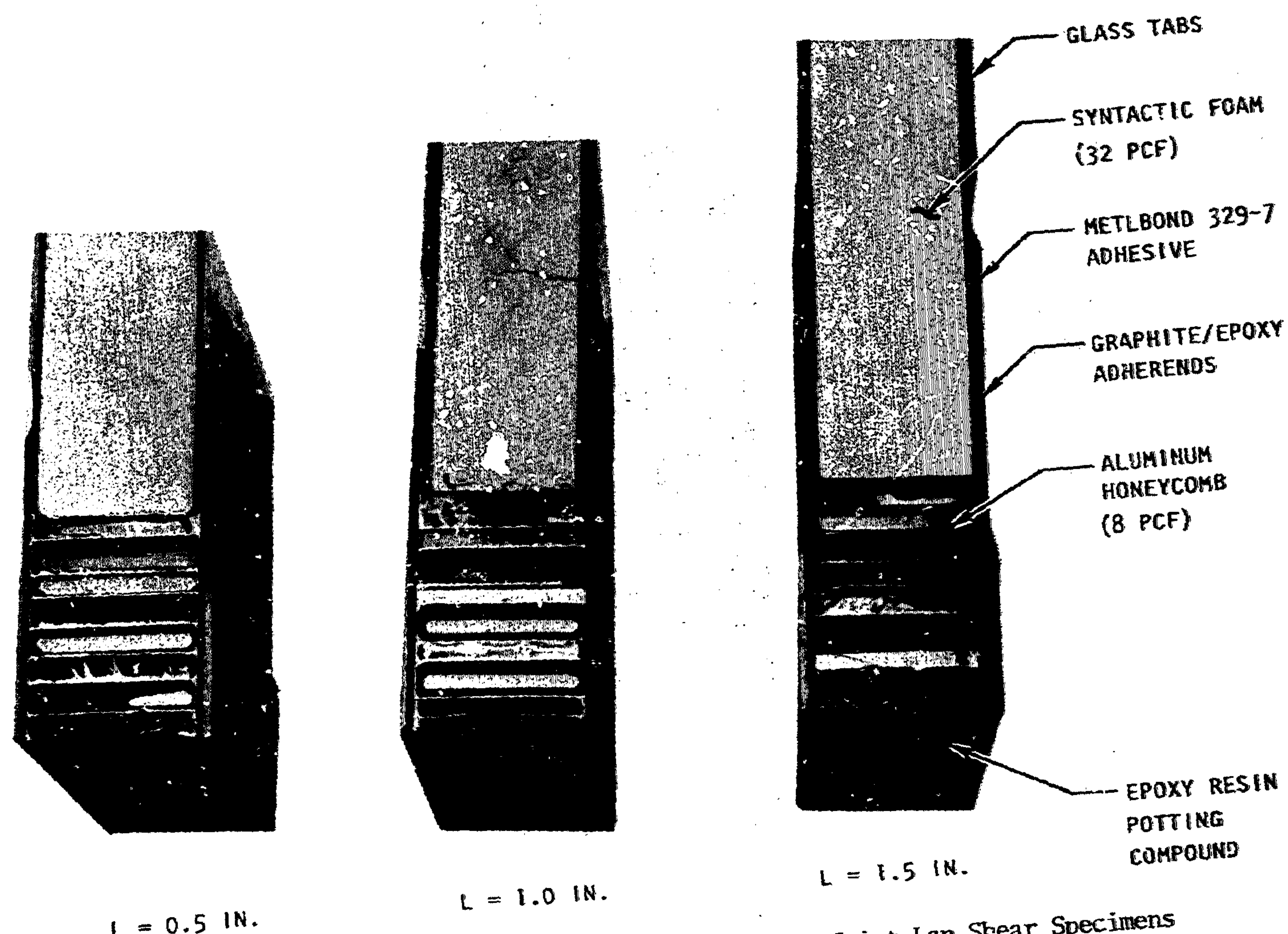


Figure 18. Graphite-to-Graphite Sandwich Compression Bonded Joint Lap Shear Specimens

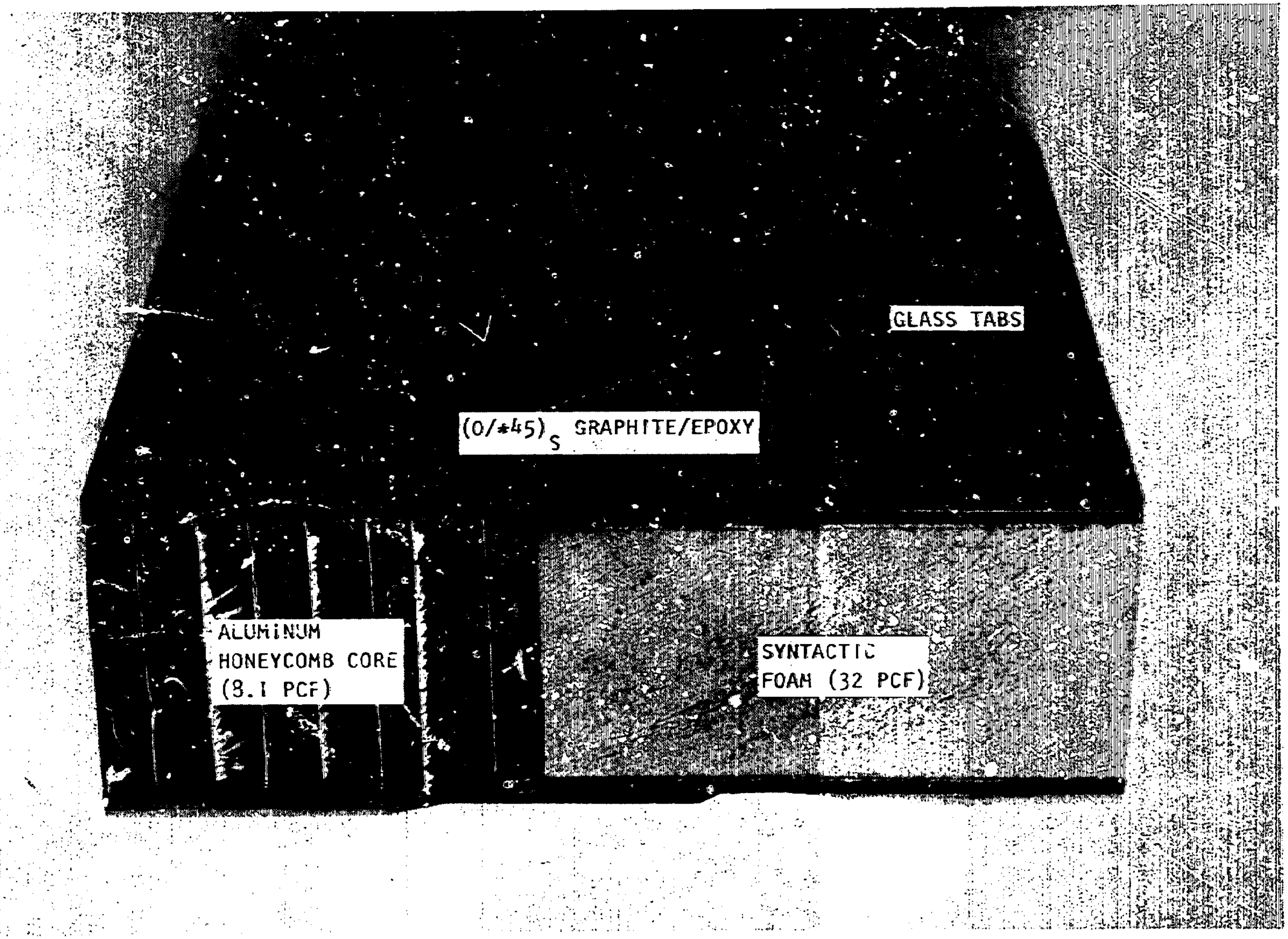
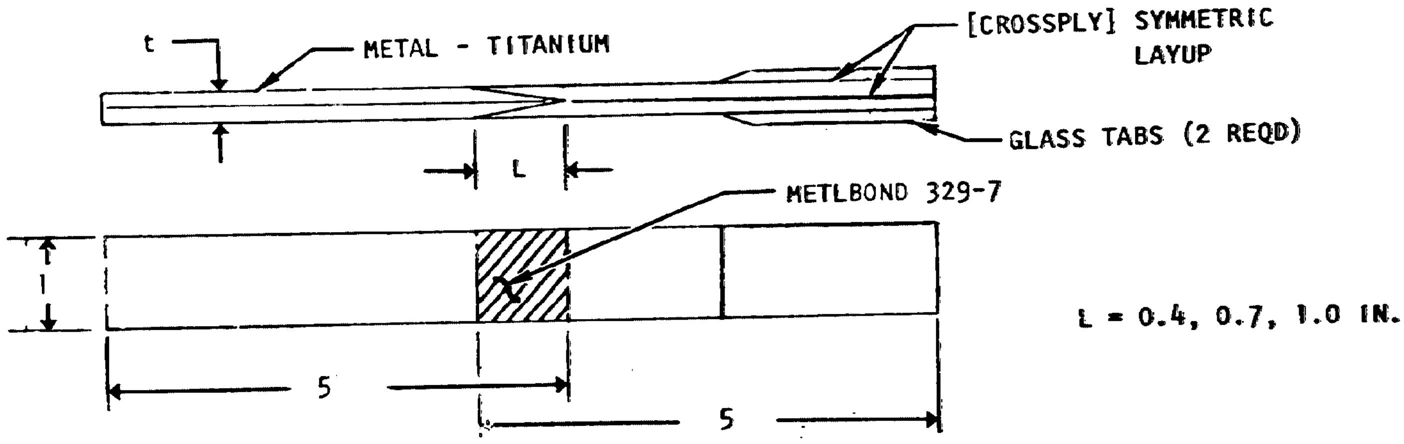


Figure 19. Compression Adhesive-Bonded Lap Joint Test Specimen - Graphite/Epoxy Adherends (Type AS/3002 Batch), Adhesive Metlbond 329-7

BONDED JOINT (TENSION-SCARF COUPON) COMPOSITE TO METAL



<u>CONFIGURATION TYPE</u> (BONDED JOINT-SCARF) GRAPHITE-TITANIUM
TBGT- (STATIC)
TBGTF- (FATIGUE)

<u>NOTES:</u>

1. ROUGHEN FAYING SURFACE AND SOLVENT CLEAN PRIOR TO BONDING.
2. CONFIGURATION FOR STATIC AND FATIGUE TESTING WILL BE THE SAME.

Figure 20. Bonded Joint - Double Scarf - Tension Specimen

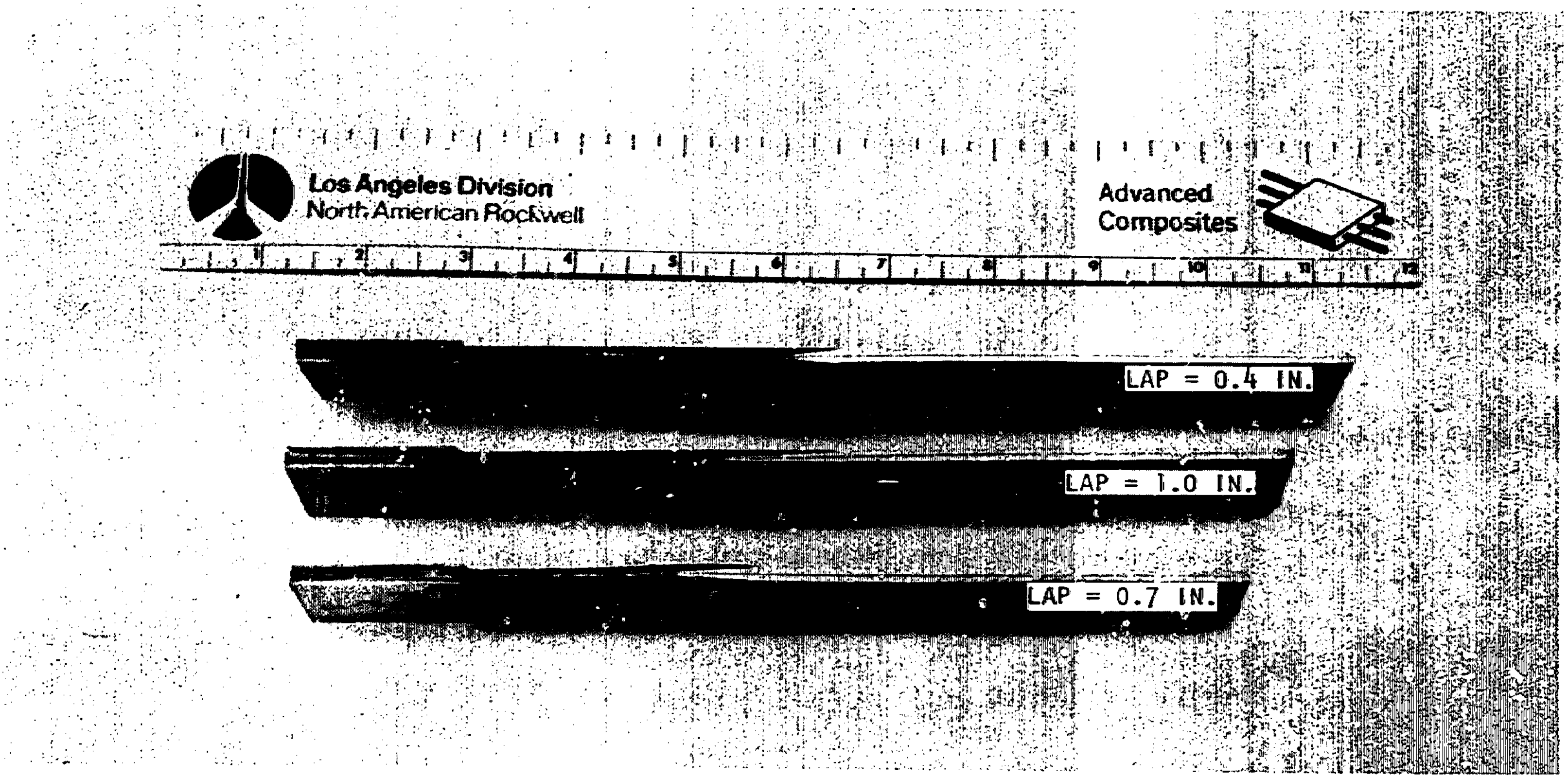
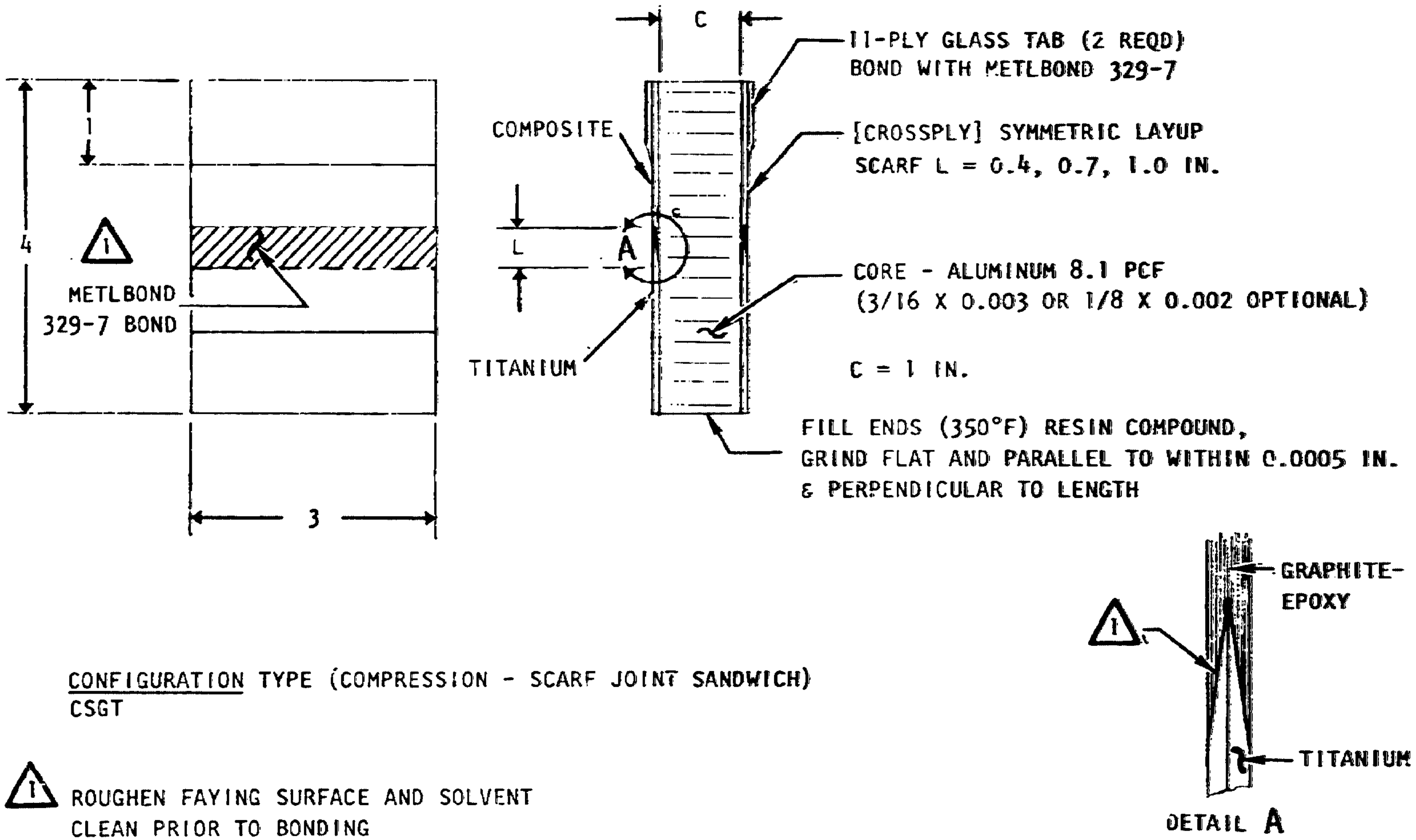


Figure 21. Adhesive-Bonded Tension Scarf Joints - Titanium to Graphite/Epoxy Adherends, Adhesive Metlbond 329-7, Lap Lengths of 0.4, 0.7, and 1.0 Inch

BONDED JOINT (COMPRESSION-SCARF-SANDWICH) COMPOSITE TO METAL



<u>CONFIGURATION</u> TYPE (COMPRESSION - SCARF JOINT SANDWICH)
CSGT

△1 ROUGHEN FAYING SURFACE AND SOLVENT CLEAN PRIOR TO BONDING

Figure 22. Bonded Joint - Double Scarf - Compression Specimen

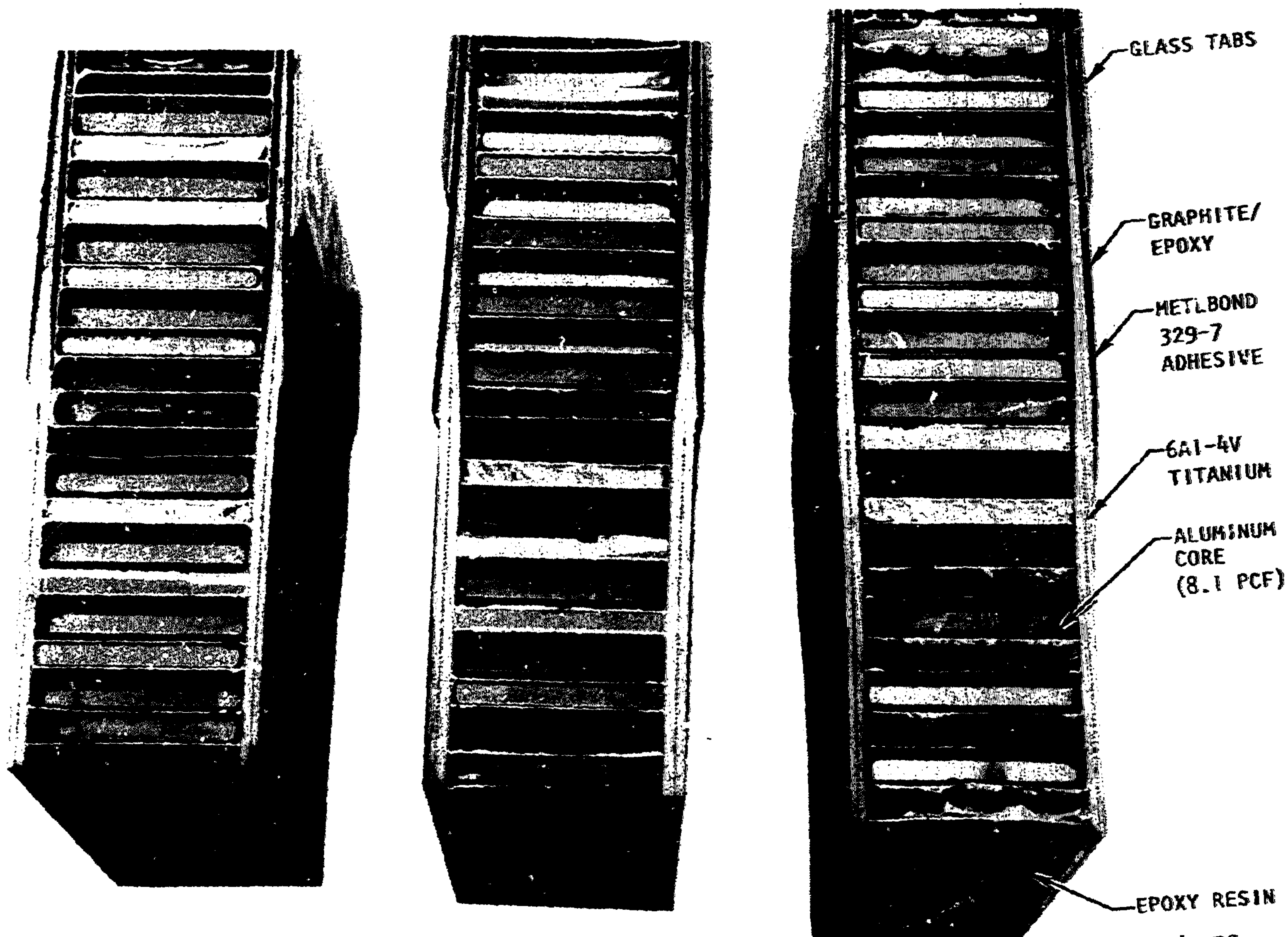


Figure 23. Graphite/Epoxy-Titanium Double Scarf Bonded Joint Short Column Compression Specimens

MECHANICAL JOINTS

Tension Specimens

Conventional single lap shear mechanical joint specimens were fabricated as shown in figure 24. The specimen configuration codes for static tests were PHT- and FHT- for protruding head (hex head) and flush head (100° countersunk), respectively. For fatigue tests, the specimen identifications are FPHT- and FFHT- for protruding and flush head mechanical joints, respectively. The mechanical joint configuration selected for prior exposure thermal cycling was the $[0/\pm45]_{4S}$ (24 plies) flush head joint designated FHTTC-24LA- .

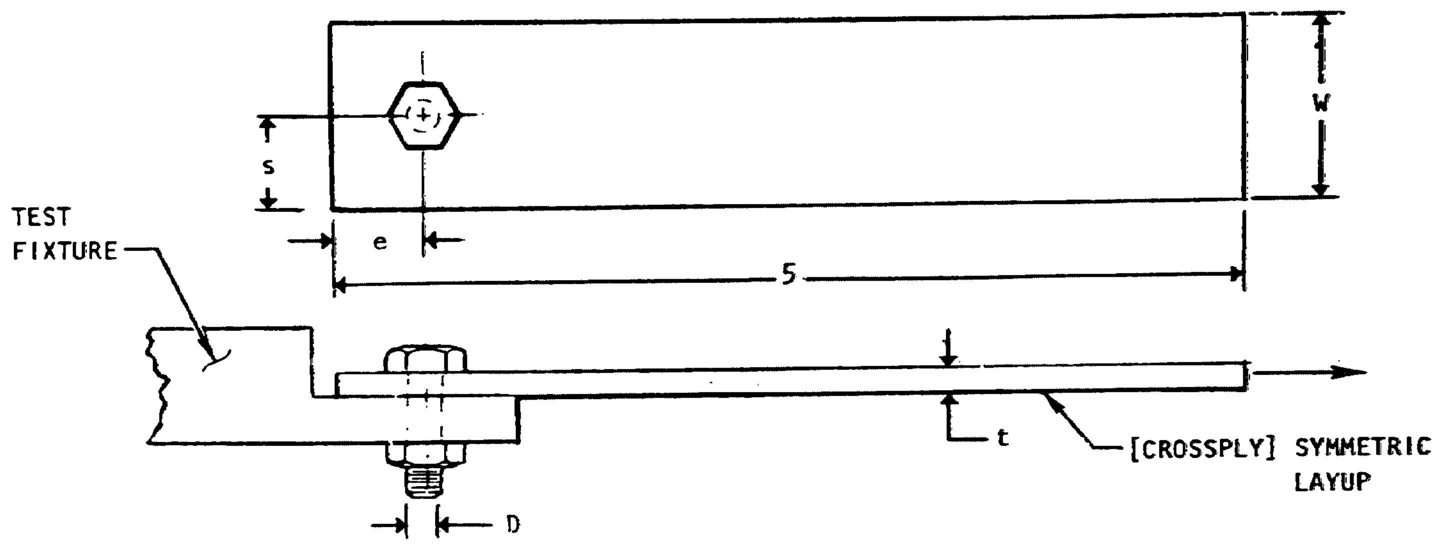
Compression Specimens

Short column sandwich mechanical joint compression specimen graphite/epoxy facings were individually slit from precured laminates and assembled onto 1.0-inch-thick syntactic foam details. Foam was utilized in this particular sandwich application to afford the capability of hand tailoring each specimen for optimum test fixture insert fitup. Graphite/epoxy face sheet parallelism was maintained in the open end of each specimen during the subsequent bonding operation with the aid of 1.0-inch-thick aluminum bar stock. End tabs (1.0-inch wide) were bonded onto the composite face sheets over the foam-supported end of each specimen, and this end was then machined flat and perpendicular to the plane of the facings. Holes were then drilled in these facings parallel to this machined edge using a suitable drill jig. (Each joint configuration had a corresponding jig fixture using the aluminum bar stock.) Each joint configuration was match drilled in these aluminum inserts, and the ends were machined parallel to these holes. These test inserts were then positioned in their respective joint specimens, using the appropriate bolts, and the syntactic foam in each specimen was individually hand filed to insure proper fit prior to test. (See figures 25 and 26.)

THERMAL-PHYSICAL CONSTANT SPECIMENS

Fluids permeability, coefficient of thermal expansion, thermal conductivity, and heat capacitance specimens required only laminate machining to specimen configuration with no subassembly operations. (See figure 27.)

MECHANICAL JOINT (TENSION - SINGLE LAP SHEAR) 1 X 5



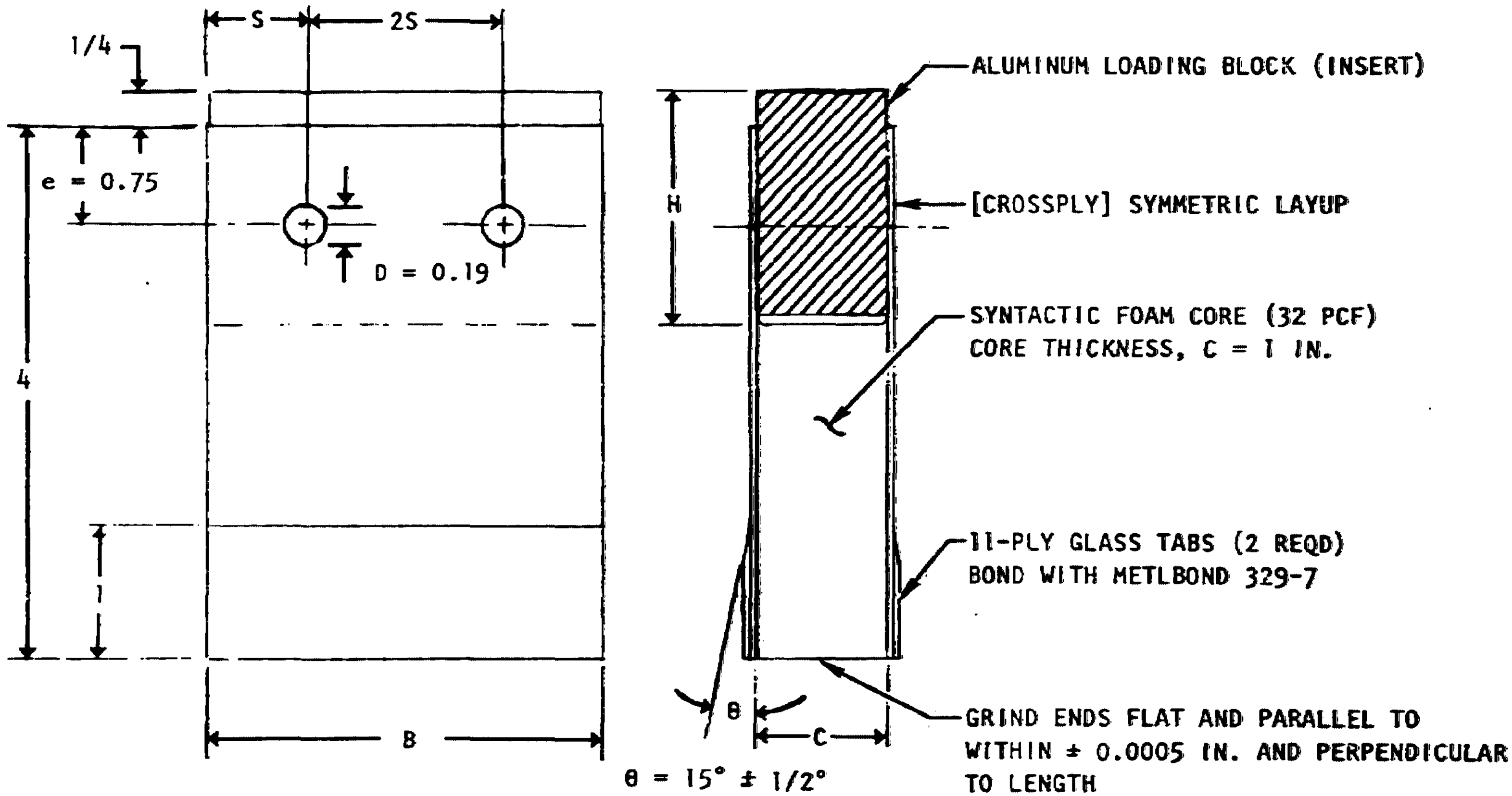
NOTES:

1. CONFIGURATION FOR STATIC AND FATIGUE TESTING WILL BE THE SAME.
2. s AND e DIMENSIONED FOR [0/±45/90] LAYUP; MAY VARY FOR OTHER CROSSPLIES.

CONFIGURATION STATIC	FASTENER	W	s	e	D	NUMBER OF PLIES
PHT-1	PROTRUDING HEAD	1.00	0.50	0.50	0.190	8
PHT-2	(NAS1303 OR	1.00	.50	.75	.190	8
PHT-3	EQUIV)	1.00	.50	1.00	.190	8
FHT-1	FLUSH HEAD	1.00	.50	.50	.190	16
FHT-2	(NAS1153 OR	1.00	.50	.75	.190	16
FHT-3	EQUIV)	1.00	.50	1.00	.190	16

Figure 24. Mechanical Joint - Single Lap - Tension Specimen

MECHANICAL JOINT (COMPRESSION - SINGLE LAP - SANDWICH)



CONFIG	S	B	H	FASTENER
PHC-1	.50	2.0	1.75	PROTRUDING HEAD (NAS 1303)
PHC-2	.75	3.0	1.75	
PHC-3	1.00	4.0	1.75	

CONFIG	S	B	FASTENER
FHC-1	.50	2.0	FLUSHHEAD (NAS 1203)
FHC-2	.75	3.0	
FHC-3	1.00	4.0	

Figure 25. Mechanical Joint - Lap - Compression Specimen

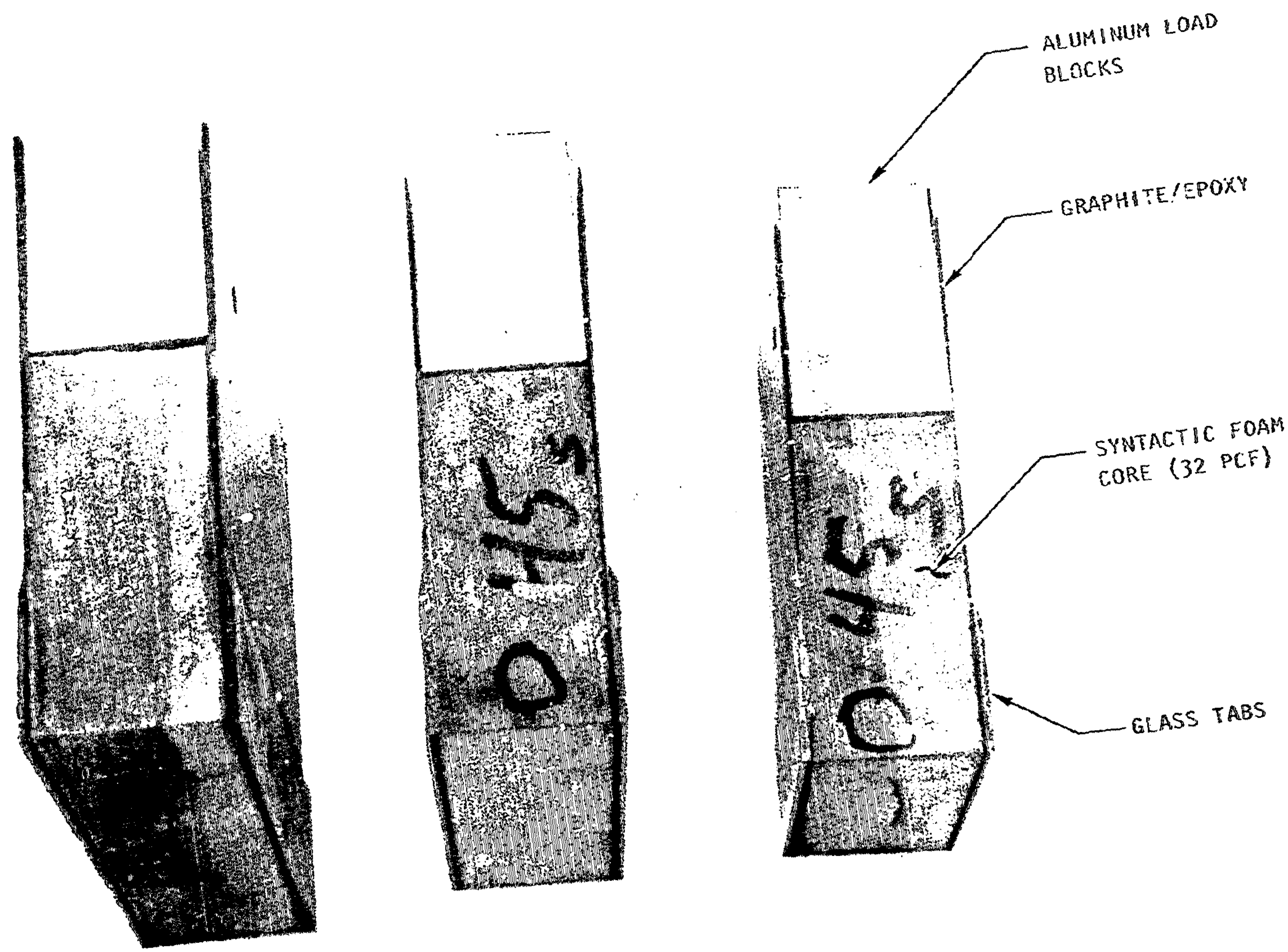


Figure 26. Graphite/Epoxy Short Column Compression Mechanical Joint Specimens

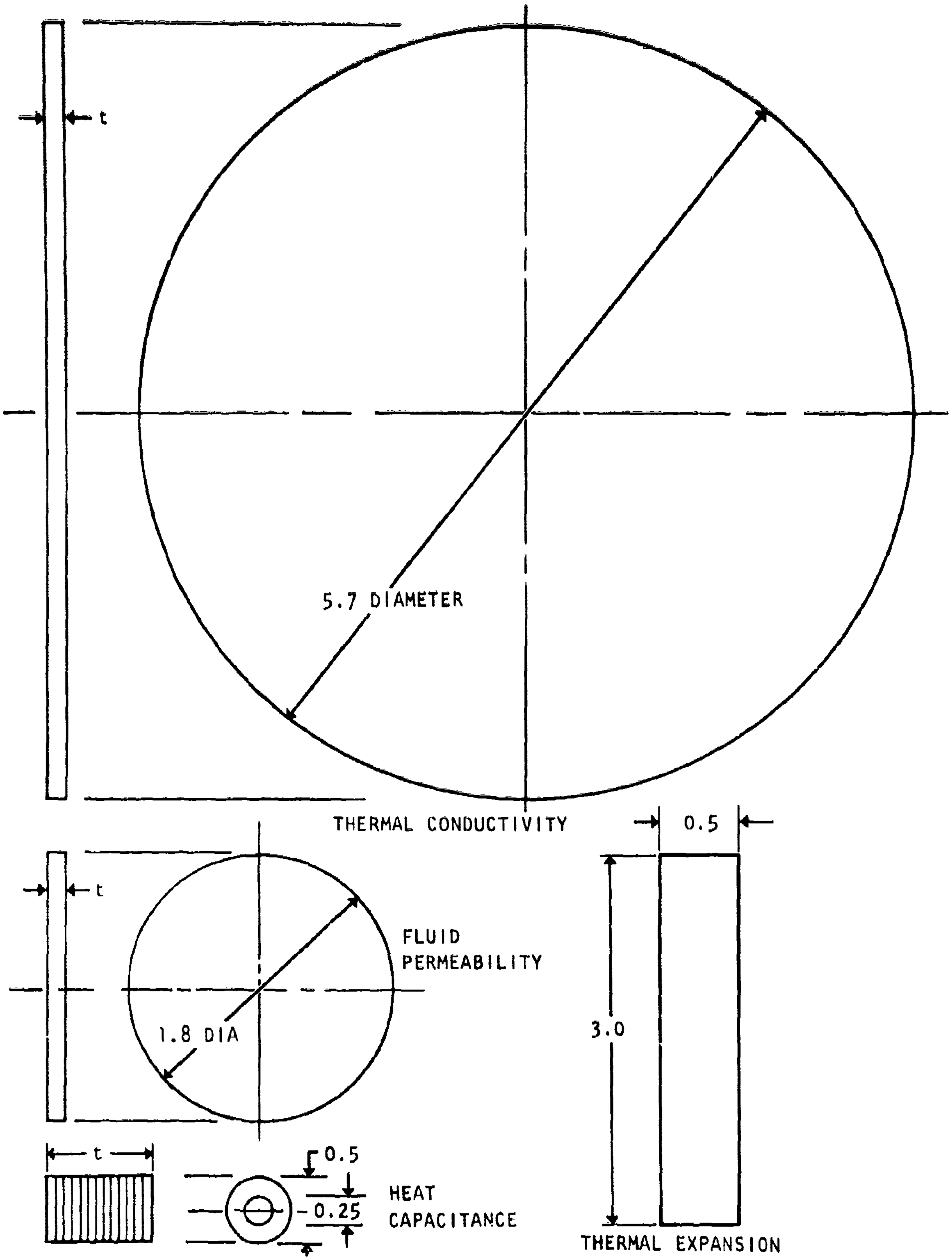


Figure 27. Graphite/Epoxy Thermal Physical Constant Specimen Configurations

SECTION IV

TESTING AND DATA EVALUATION

GENERAL

The graphite/epoxy characterization effort, summarized in tables I, II, and III, was divided into two categories: baseline data and environmental effects data.

The objectives of the baseline data test program were to provide the pertinent static and fatigue properties of Type AS/3002 batch graphite/epoxy to support the basic design of graphite/epoxy airframe structural components. The baseline data include the following items:

1. Basic mechanical properties of unidirectional and crossplied laminates

2. Joint data of bonded single lap, bonded double scarf, and mechanical-single lap configurations

3. Fundamental configuration data of sandwich structure with various honeycomb core densities, open hole specimens, and thickness buildup tension coupons

The purpose of the environmental effects tests was to determine the influence of the typical operating environment of high-performance aircraft on the design allowables of graphite/epoxy materials.

Tables I and II outline the baseline data and environmental effects test program, detailing the load conditions, specimen types, laminate orientations, quantity of specimens, test temperatures, and environments. Specimen configuration details are shown in figures 2 through 27.

The following brief summary indicates the scope of the test program.

1. Baseline data

	Quantity	Type Loads
Mechanical properties-unidirectional	85	Tension, compression, shear
Mechanical properties-crossplied	157	Tension, compression, shear
Bonded joints	198	Tension, compression
Mechanical joints	138	Tension, compression
Configuration specimens	143	Tension, compression
Total	721	

2. Environmental Effects

	Quantity	Type Loads
Thermal cycling	45	Quality control, tension
Nuclear Radiation	27	Quality control
Nuclear thermal pulse	12	Tension, compression
Humidity, salt spray, weathering, permeability	84	Quality control
Thermal aging	63	Quality control
Thermal physical constants	24	Thermal
Total	255	

The baseline data tests utilized room (70°F), elevated (350°F) and subzero (-65°F) test temperatures, while the environmental tests were generally conducted at room temperature and 275°F as indicated in tables I and II.

A total of 134 specimens were tested as an initial characterization effort involving untreated fiber Type A/3002 batch graphite/epoxy as shown in table III. The 36 bonded and 30 mechanically fastened joint data points are included in baseline data program, while the remaining 78 data points are reported in this section as supplementary data to augment the treated fiber - Type AS/3002 graphite/epoxy data generation effort. In addition, 10 crossplied tension sandwich beams of Type AS/3002 graphite/epoxy are reported which were tested under IR&D funding.

All tests were conducted using existing test fixtures, instrumentation, and testing machines previously utilized on the boron/epoxy test program (references 4 and 5). All static tests, with the exception of sandwich beam and quality control tests were conducted on a Riehle FS-60W Universal testing machine which has a variable load scale to permit changing scales with no interruption in load application. The sandwich beam tests were conducted on a Riehle PS-120 Universal testing machine which allowed the accommodation of the sandwich beam test fixture. The quality control type tests for interlaminar shear (short beam shear) and longitudinal flexure were conducted on a Tinius-Olsen Universal Testing machine of 10,000-pound capacity using the test fixture described in figures 1 and 2 of reference 4.

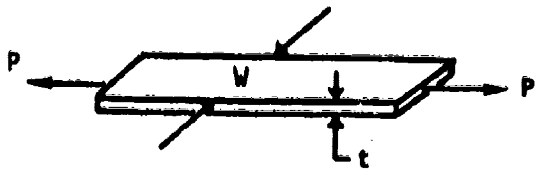
Fatigue tests were conducted basically on two machines, a ±12,000-pound capacity Baldwin-Lima-Hamilton IV-12 at a cycling rate of 1,200 cpm and an Amsler Vibrophore with a ±4,400-pound dynamometer at a cycling rate of 93 cps.

Load-deflection data of most of the tension coupon and sandwich edgewise compression specimens were obtained using conventional extensometers. In addition, strain gages were used on specimens so designated in the test data summary tables. Stress-strain data were obtained using strain gages for the sandwich beam and rail shear tests.

DATA REDUCTION FORMULAE

The following set of equations was used for the different types of specimens tested:

1. Tension Coupons:



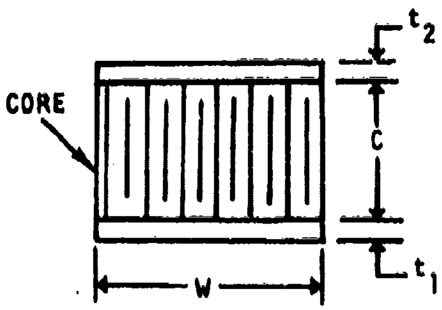
$$f^{tu} = P/wt$$

where

P = failure load in pounds

E = stress/strain = f/ϵ

2. Sandwich Bending Beams:

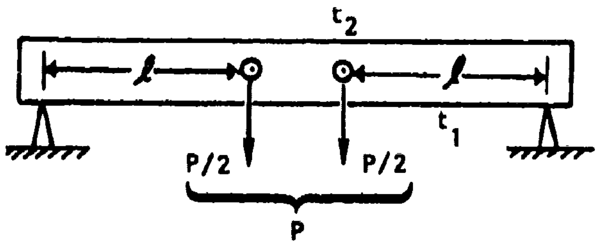


Tension test (t_1 is laminate)

$$f^{tu} = \frac{P\ell}{2t_1w\left(C + \frac{t_1}{2} + \frac{t_2}{2}\right)}$$

Compression test (t_2 is laminate)

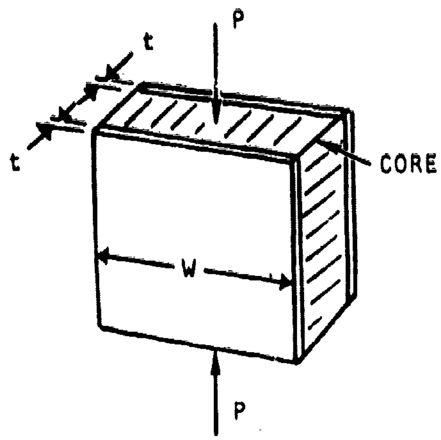
$$f^{cu} = \frac{P\ell}{2t_2w\left(C + \frac{t_1}{2} + \frac{t_2}{2}\right)}$$



where

P = failure load in pounds
Dimensions in inches

3. Edgewise Compression Specimens:

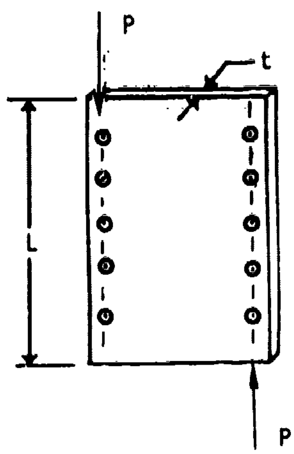


$f^{cu} = P/2wt$

where

P = failure load in pounds
Dimensions in inches

4. Rail Shear Specimens:



$f^{su} = P/Lt$

where

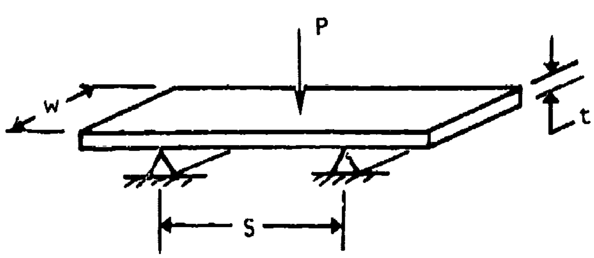
P = failure load in pounds

$$G = \frac{\text{shear stress}}{\text{shear strain}} = \frac{f^s}{\gamma}$$

Dimensions in inches

5. Interlaminar Shear Specimens:

$$f^{isu} = \frac{3P}{4wt}$$

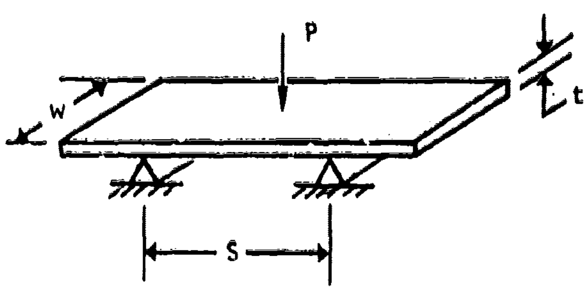


where

P = failure load in pounds

Dimensions in inches

6. Flexure Specimens:



$$f^{flex\ ult} = \frac{3PS}{2Wt^2}$$

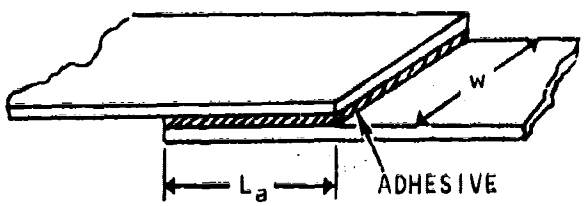
where

P = failure load in pounds

Dimensions in inches

7. Bonded Joints (Adhesive Shear Stress):

a. Single Lap Joint Specimens:



$f_a^{su} = P/wL_a$ (tension)

where

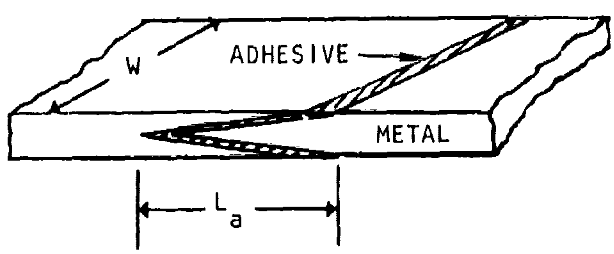
P = failure load in pounds

Dimensions in inches

NOTE: For compression sandwich specimens, there were two face sheets (one joint per face sheet) and, hence, the formula must be divided by 2:

$$f_a^{su} = P/2wL_a$$

b. Symmetric Double Scarf Joint Specimens:



$f_a^{su} = P/2wL_a$ (tension)

where

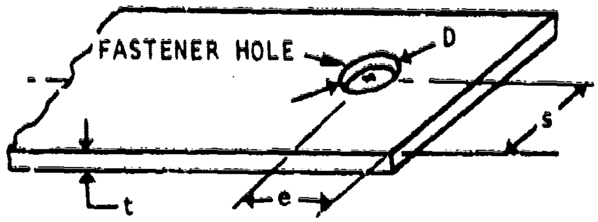
P = failure load in pounds

Dimensions in inches

NOTE: For compression sandwich specimens, there were two face sheets (one joint per facesheet) and, hence, the formula must be divided by 2:

$$f_a^{su} = \frac{P}{4wL_a}$$

8. Mechanical Joint:



Bearing stress

$$f^{bru} = P/Dt$$

Net tension stress

$$f^{tu} = \frac{P}{2Dt\left(\frac{s}{D} - 0.5\right)}$$

P = failure stress for appropriate mode of failure

Dimensions in inches

Shearout stress

$$f^{su} = \frac{P}{2Dt\left(\frac{e}{D} - 0.5\right)}$$

NOTE Compression mechanical joints all failed in bearing; hence, bearing stress is defined as

$$f^{bru} = P/DtN$$

where

N = number of fasteners

MECHANICAL PROPERTIES

UNIDIRECTIONAL PROPERTIES

Tension Properties

Treated Graphite Fiber Laminates (Type AS/3002)

Tables VIII and IX present longitudinal and transverse tension data from IITRI coupon tests as well as sandwich bending beams for Type AS/3002 batch graphite/epoxy unidirectional laminates. Three test temperatures were used, namely, -65°F, 70°F (room temperature), and 350°F. Ultimate strength, initial modulus, and ultimate strain values are presented, with the strength and modulus values being compared to predicted values from the design allowables section. In general, all the test strength values compared well with predicted strengths, with the exception of the room temperature transverse tension strength obtained from the sandwich bending beam test, which was three

TABLE VIII. UNIDIRECTIONAL GRAPHITE/EPOXY LONGITUDINAL TENSION DATA (TYPE AS/3002 BATCH)

Test Orientation	Specimen No.	Thickness (in.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus (Msi)	Ultimate Strain (μ in./in.)	Test/Predicted Strength	Test/Predicted Modulus
$[0]_{6T}$	T-UL-7	0.0375	-65	109.3	19.1	5,700	0.68	1.12
Longitudinal	T-UL-8	0.0356	-65	129.8	19.6	6,600	0.81	1.15
tension	T-UL-9	0.0360	-65	122.2	16.4	7,200	0.76	0.97
coupon	Avg			(120.4)	(18.4)	(6,500)	(0.75)	(1.08)
6 plies	T-UL-10	0.0340	RT	130.4	18.6	6,795 SG	0.82	1.09
	T-UL-11	0.0378	RT	160.3	19.3	8,270	1.00	1.14
	Avg			(145.4)	(18.9)	(7,533)	(0.91)	(1.11)
	T-UL-12	0.0370	350	166.2	19.9	8,810** SG	1.15	1.24
	T-UL-13	0.0399	350	135.0	17.7	7,610	0.94	1.01
	T-UL-14	0.0376	350	154.3	18.2	8,480	1.07	1.14
	Avg			(151.8)	(18.6)	(8,300)	(1.05)	(1.16)
$[0]_{6T}$	TLBB-UL2	0.0360	-65	152.9	No data	No data	0.96	No data
Longitudinal	TLBB-UL17	0.0360	-65	159.4	No data	No data	1.00	No data
tension	Avg			(156.1)			(0.98)	
sandwich bending beam*	TLBB-UL1	0.0360	RT	190.6	19.6	>10,500	1.19	1.15
	TLBB-UL16	0.0360	RT	183.0	No data	No data	1.14	No data
6 plies	Avg			(186.8)	(19.6)	(>10,500)	(1.17)	(1.15)

NOTE: * Sandwich beam with one face sheet of steel and one face sheet of secondary bonded graphite/epoxy (adhesive: Metlbond 329-7)

** Tab delaminated and test stopped on first run; tab reworked and test rerun; rerun values quoted.

SG = strain gage value; all other values are extensometer values.

TABLE IX. UNIDIRECTIONAL GRAPHITE/EPOXY TRANSVERSE TENSION DATA (TYPE AS/3002 BATCH)

Test Orientation	Specimen No.	Thickness (in.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus (Msi)	Ultimate Strain (μ in./in.)	Test/Predicted Strength	Test/Predicted Modulus
$[90]_{6T}$ Transverse tension coupon	T-UT-7	0.0340	-65	10.43	No data	No data	1.39	No data
	T-UT-8	0.0367	-65	5.24	No data	No data	0.70	No data
	T-UT-9	0.0351	-65	7.32	No data	No data	0.98	No data
	Avg			(7.66)			(1.02)	
6 plies	T-UT-10	0.0370	RT	8.36	0.690	12,504 SG	1.12	0.41
	T-UT-11	0.0370	RT	9.56	No data	No data	1.28	No data
	T-UT-12	0.0354	RT	9.22	No data	No data	1.23	No data
	Avg			(9.05)	(0.690)	(12,504)	(1.21)	(0.41)
	T-UT-13	0.0350	350	3.41	0.714	6,700** SG	0.85	0.71
	T-UT-14	0.0354	350	4.82	No data	No data	1.21	No data
	T-UT-15	0.0351	350	3.90	No data	No data	0.98	No data
	Avg			(4.04)	(0.714)	(6,700)	(1.01)	(0.71)
$[90]_{6T}$ Transverse tension sandwich bending beam* 6 plies	TLBB-UT1	0.0360	RT	22.9	3.7	>6,800	3.05	2.18
	Avg			(22.9)	(3.7)	(>6,800)	(3.05)	(2.18)

NOTE * Sandwich beam with one face sheet of steel and one face sheet of secondary bonded graphite/epoxy (adhesive: Metlbond 329-7)

** Estimated ultimate strain

SG = strain gage value; all other values are extensometer values.

times the predicted value. The longitudinal tension modulus values also compared well with predicted values, whereas the transverse tension moduli varied from the predicted values, as can be seen in table IX.

Figures 28 and 29 show typical failed test specimens for unidirectional Type AS/3002 batch graphite/epoxy laminates, while figures 30, 31, and 32 present typical tension stress-strain curves for -65°F, room temperature, and 350°F, respectively. The unidirectional compression stress-strain data are also included in figures 30, 31, and 32. Figure 33 presents a plot showing the effect of temperature on tensile ultimate for Type AS/3002 batch graphite/epoxy unidirectional laminates. As expected, the strength decreases with increasing temperature.

Figures 34, 35, and 36 present tension stress-strain curves as well as plots of Poisson's ratio versus strain for Type AS/3002 continuous fiber unidirectional laminates tested in tension.

These plots are included for information as the "continuous" fiber was only tested for an initial assessment of "treated" (Type AS/3002) material. Comparisons of "batch" data with "continuous" data for the treated fiber systems shows no conclusive strength nor stiffness differences.

Untreated Graphite Fiber Laminates (Type A/3002)

Table X presents longitudinal and transverse tension data for unidirectional Type A/3002 (untreated) batch graphite/epoxy laminates. In general, the strength and modulus values for the longitudinal test specimens agreed well with predicted values (section V) while, on the other hand, the transverse values were decidedly lower than expected because of premature specimen failures. Typical failed specimens are pictured in figure 37 for room temperature and 350°F tension tests. Furthermore, longitudinal tension stress-strain curves are shown in figure 38, while a Poisson's ratio plot is presented in figure 39. Note that the strength and moduli are comparable to those of the treated fiber unidirectional composites.

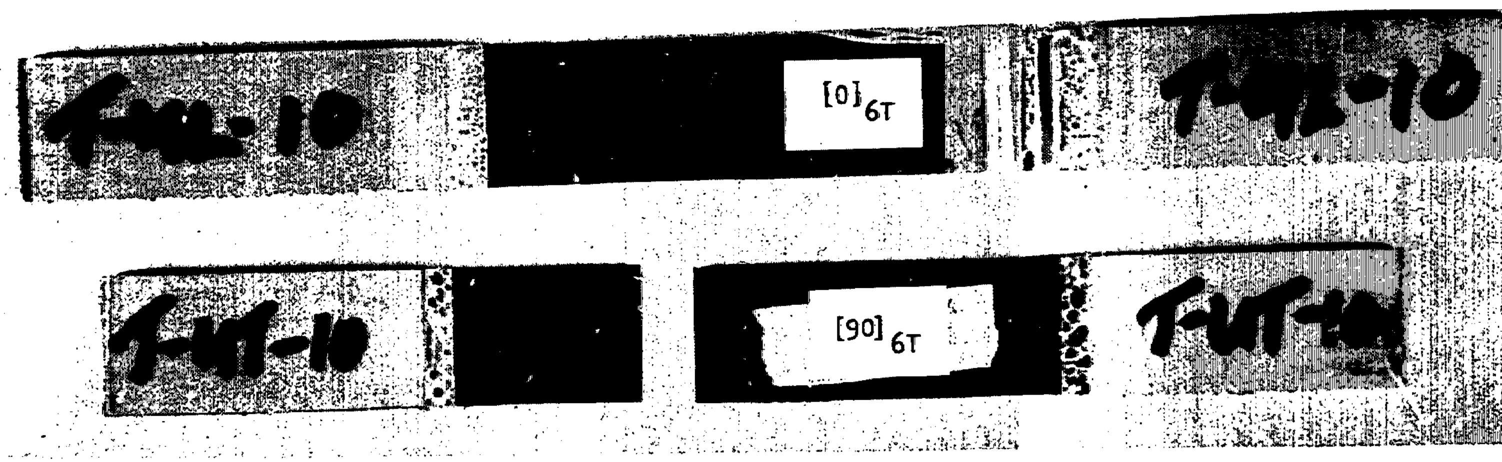


Figure 28. Typical Failed Tension Coupons - Unidirectional Graphite/Epoxy Type AS/3002 - Batch, [0] and [90] Orientation, Room Temperature

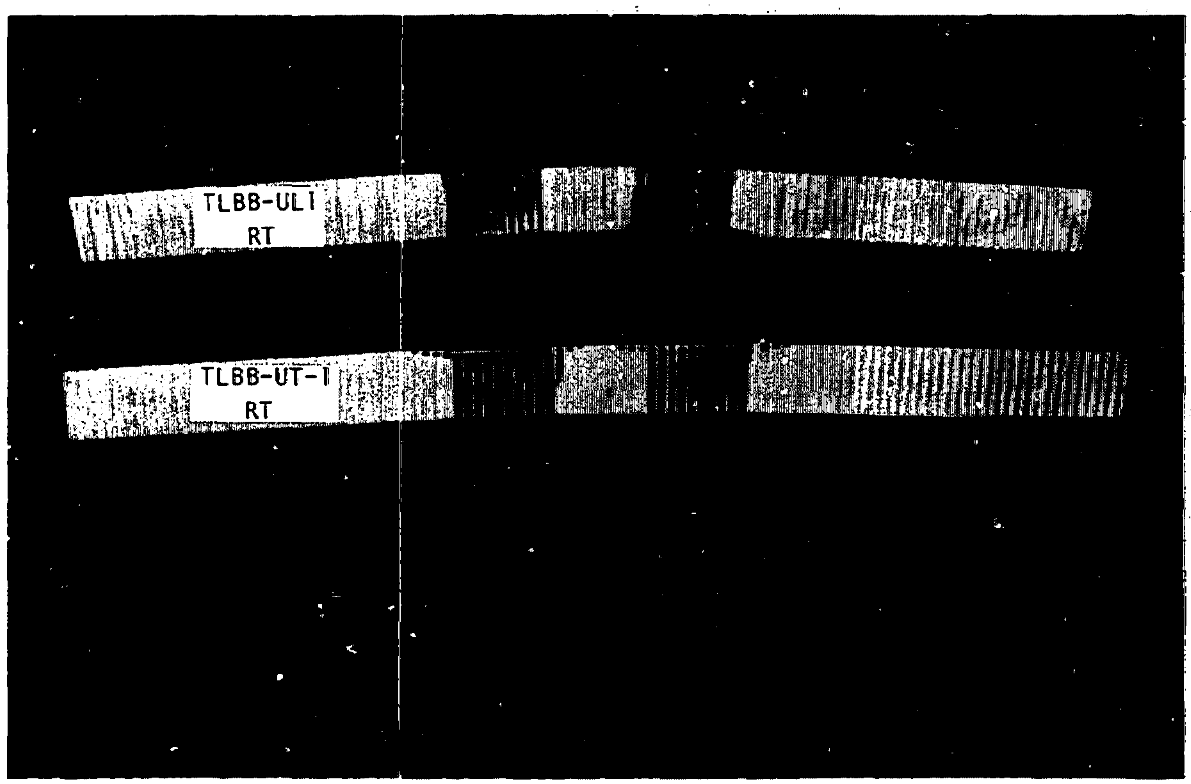


Figure 29. Longitudinal and Transverse Unidirectional Tension Sandwich Bending Beams, Type AS/3002 - Batch Graphite/Epoxy, Room Temperature

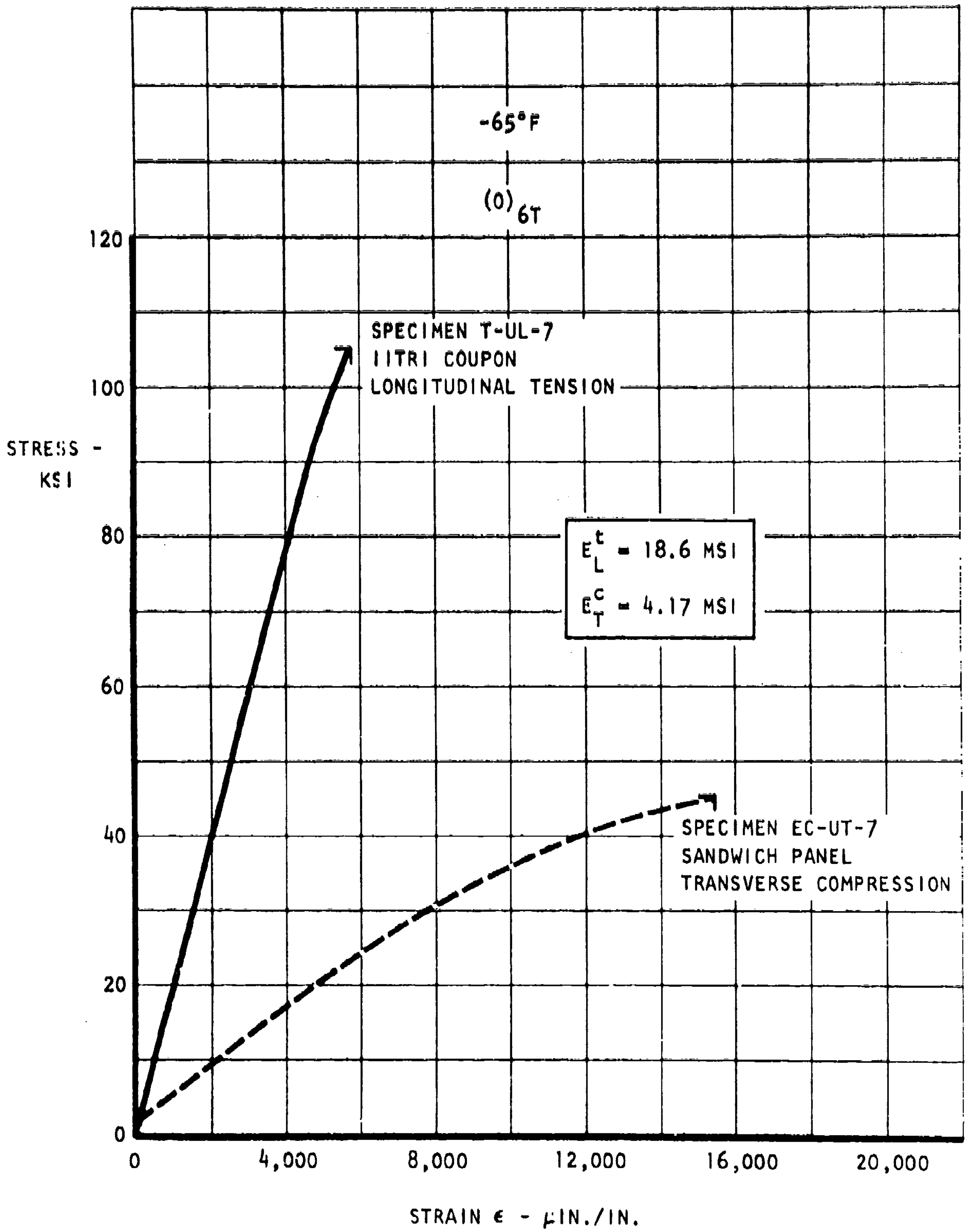


Figure 30. Unidirectional Graphite/Epoxy (Type AS/3002 - Batch) Longitudinal Tension and Transverse Compression Stress-Strain Curves at -65°F

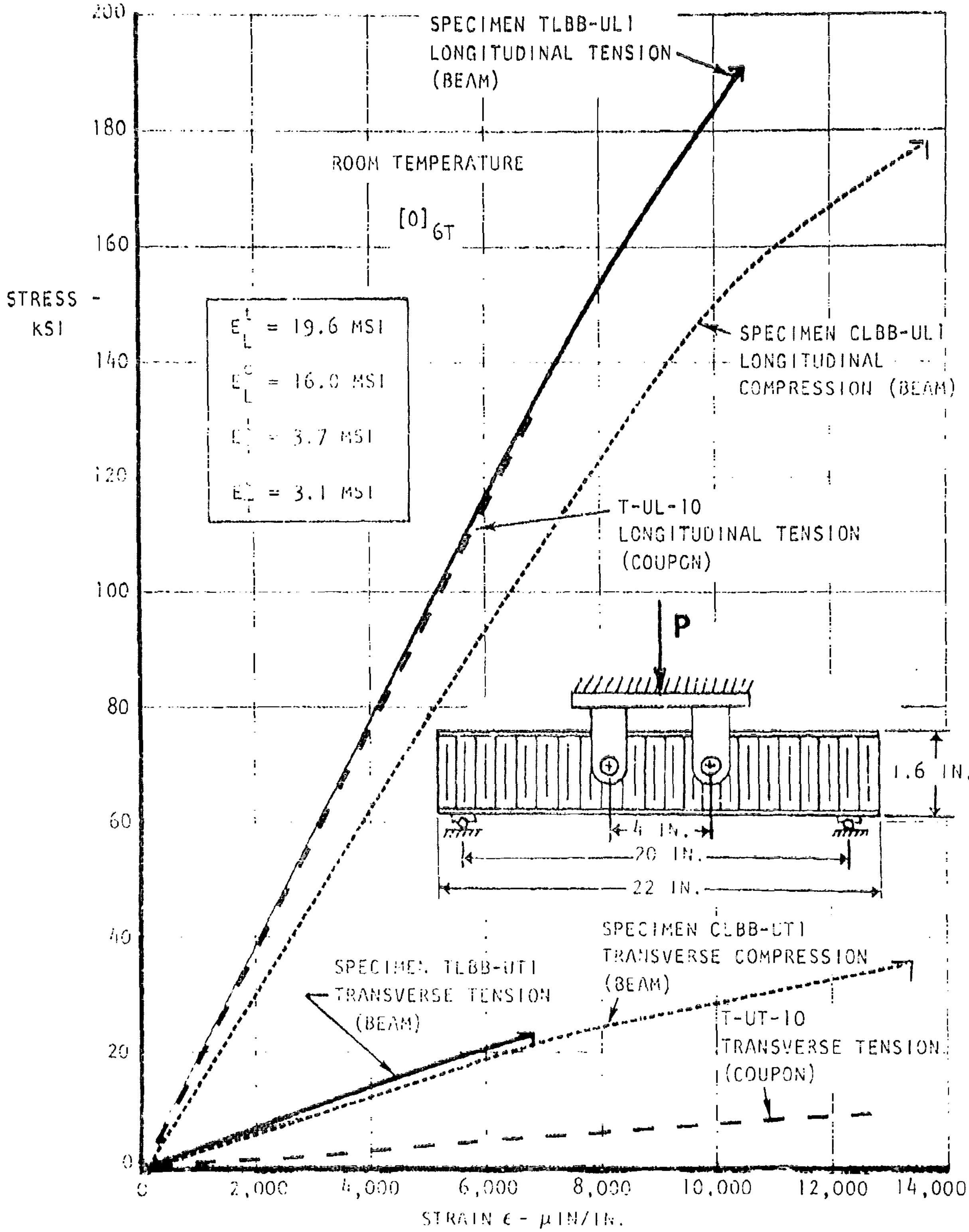


Figure 32. Unidirectional Graphite/Epoxy (Type AS/3002 - Batch) Longitudinal and Transverse Tension and Compression Stress-Strain Curves at Room Temperature

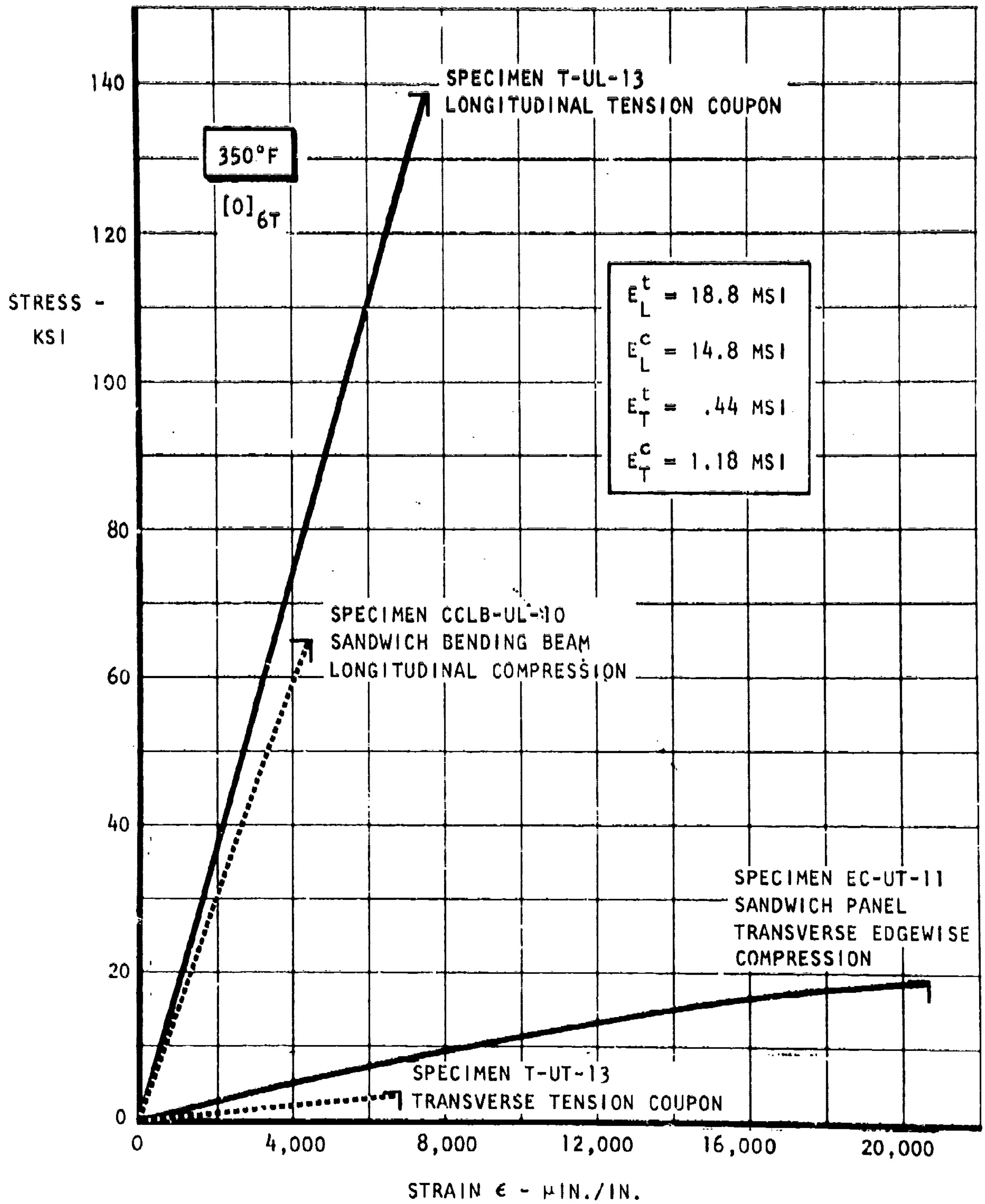


Figure 32. Unidirectional Graphite/Epoxy (Type AS/3002 - Batch) Longitudinal and Transverse Tension and Compression Stress-Strain Curves at 350°F

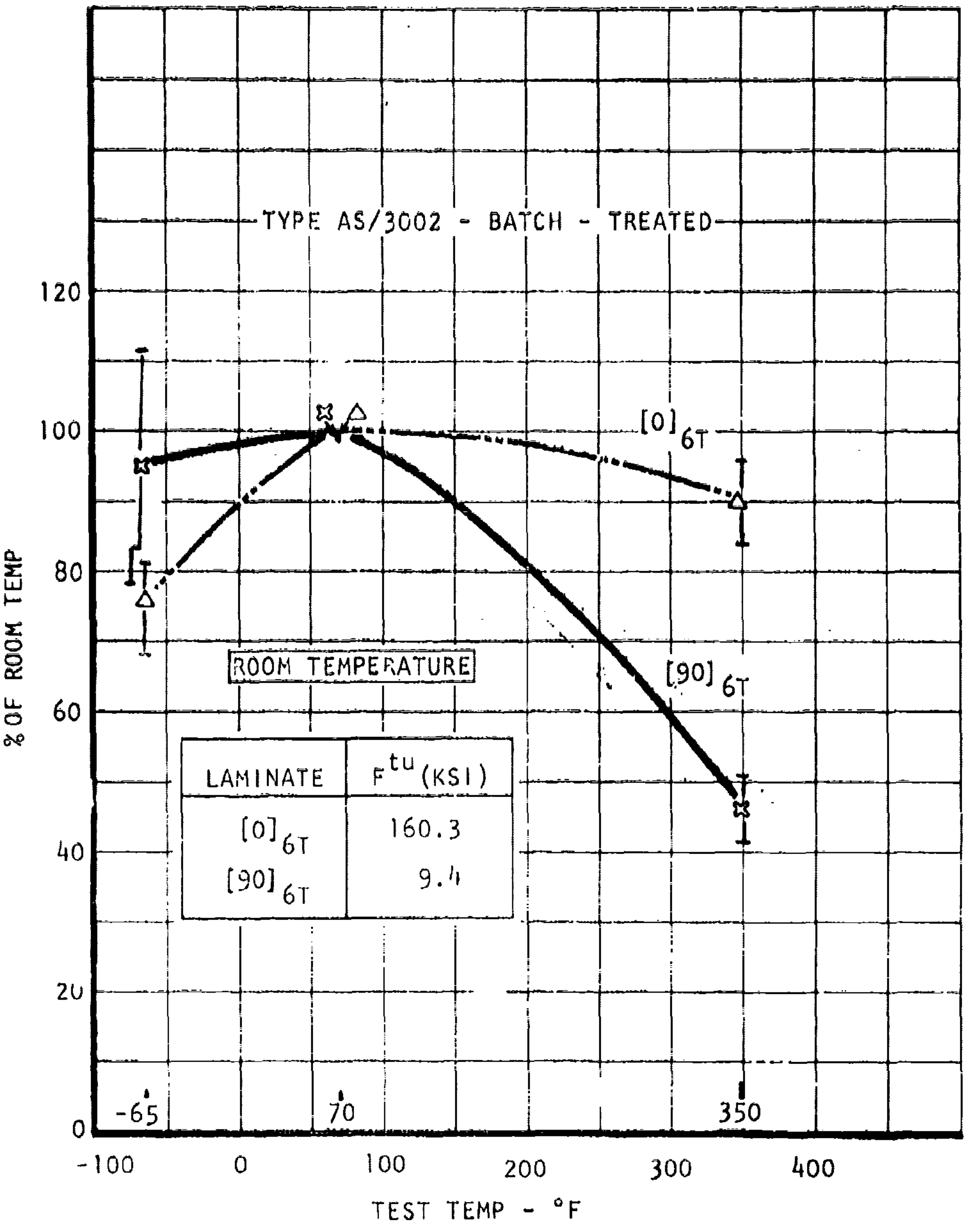


Figure 33. Graphite/Epoxy - Effect of Test Temperature on Unidirectional Properties - IITRI Coupons

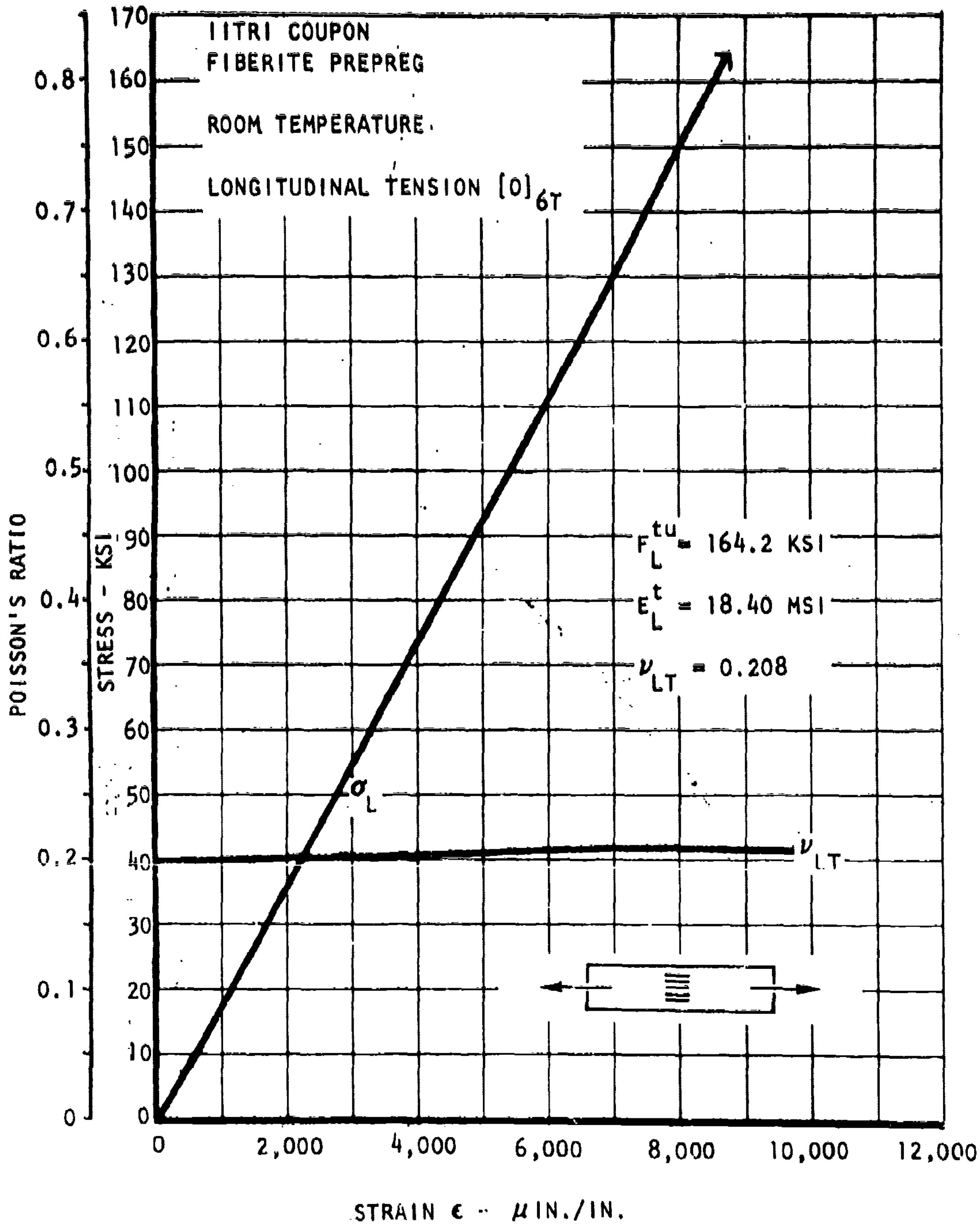


Figure 34. Graphite/Epoxy Typical Longitudinal Unidirectional Tension Stress-Strain Properties - Type AS/3002 Continuous-Treated Fiber

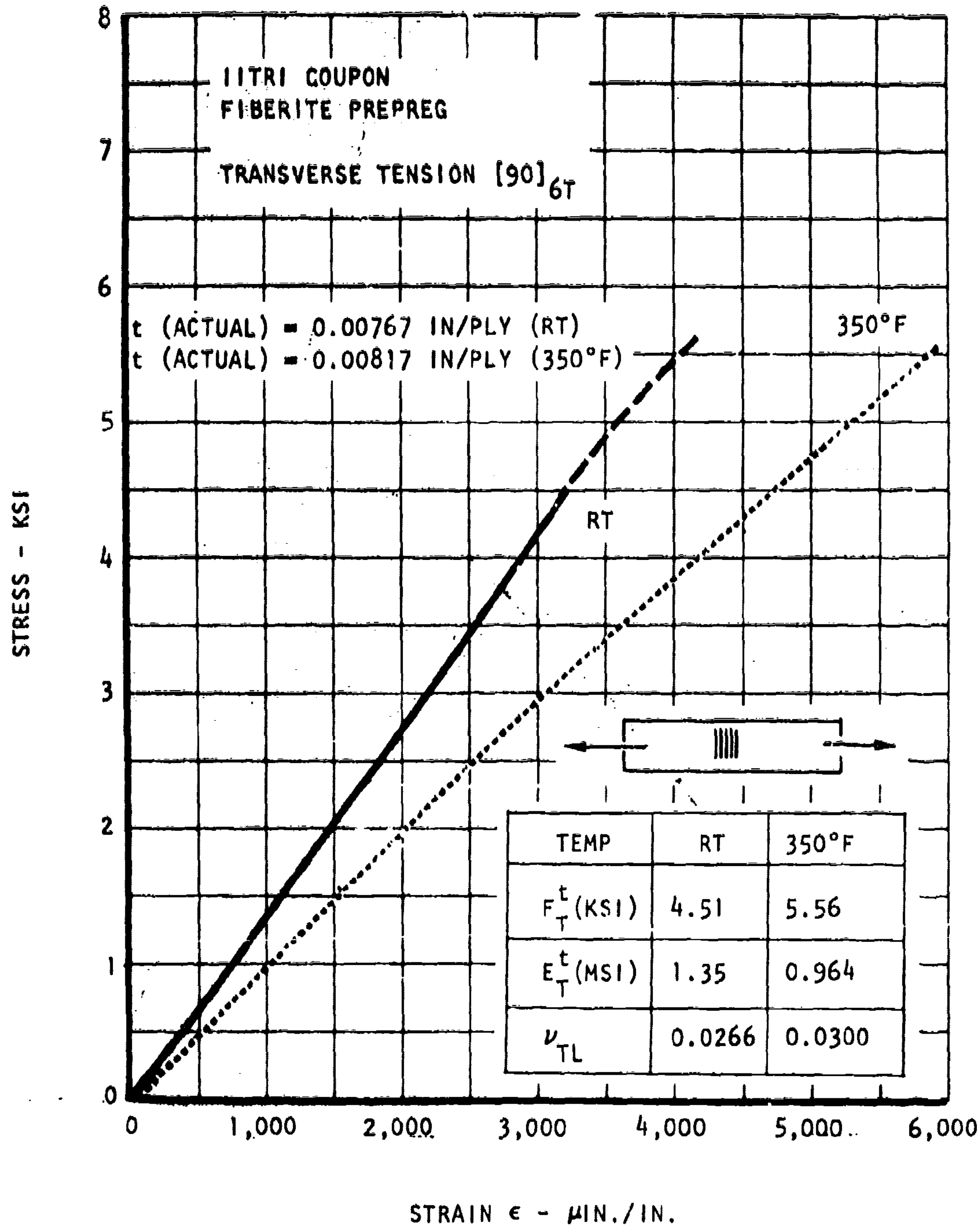


Figure 35. Graphite/Epoxy Typical Transverse Unidirectional Tension Stress-Strain Properties - Type AS/3002 Continuous-Treated Fiber

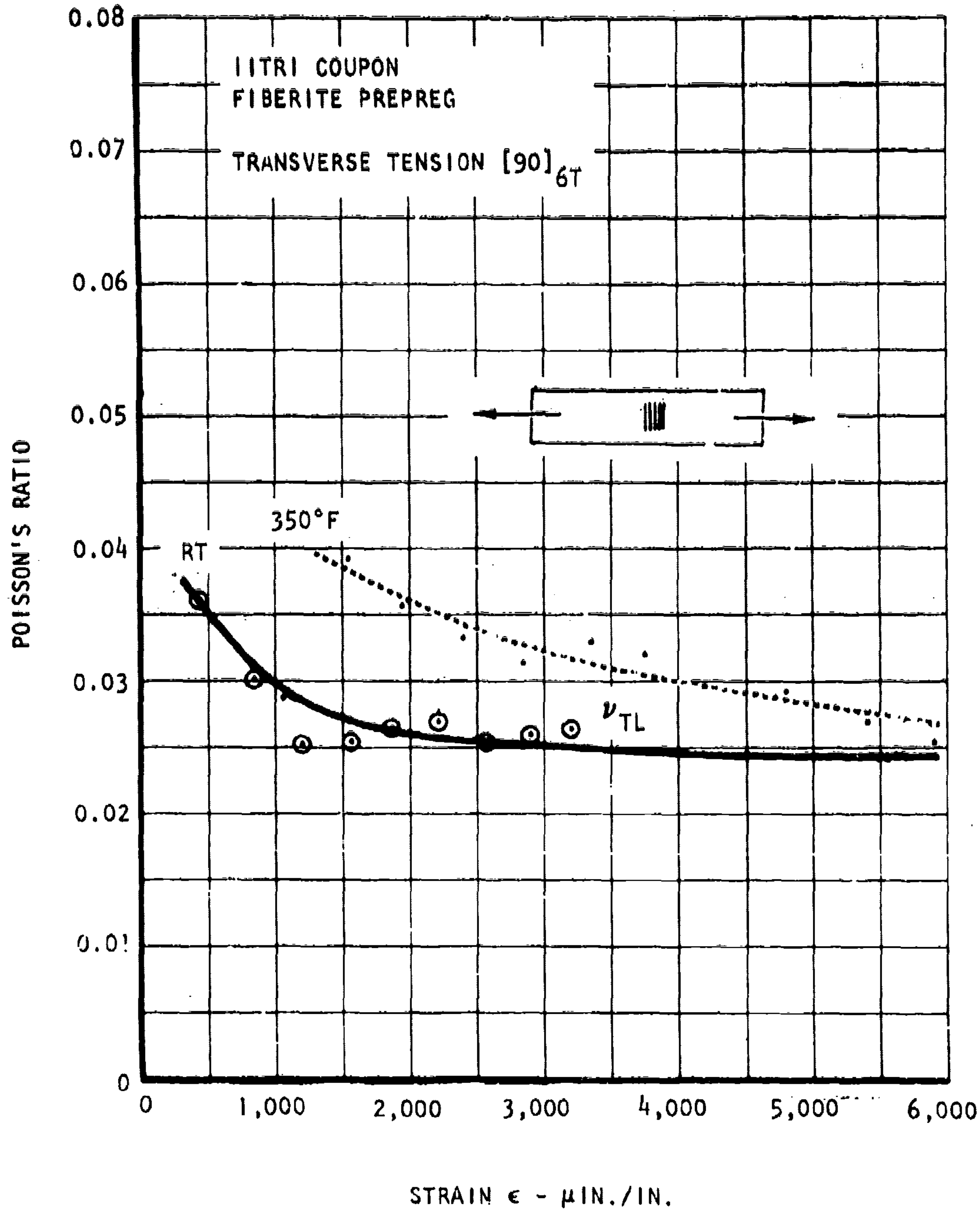


Figure 36. Graphite/Epoxy Typical Poisson's Ratios Versus Strain - Transverse Unidirectional - Type AS/3002 - Continuous-Treated Fiber

TABLE X. UNIDIRECTIONAL GRAPHITE/EPOXY TENSION DATA (TYPE A/3002 BATCH - UNTREATED FIBER)

Test Orientation	Specimen No.	Thickness (in.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus (Msi)	Ultimate Strain (μ in./in.)	Test/Predicted *** Strength	Test/Predicted *** Modulus
$[0]_{6T}$ Longitudinal tension coupon 6 plies	T-UL-1	0.037	RT	147.2	19.3*	7,600	.920	1.135
	T-UL-2	0.039	RT	162.1	17.8*	9,200	1.013	1.047
	Avg			(154.6)	(18.6)		(.966)	(1.091)
	T-UL-3	0.038	350	139.1	17.6*	7,980	.966	1.100
	T-UL-4	0.037	350	147.6	17.7**	8,350	1.025	(1.106)
	Avg			(143.4)	(17.6)		(.996)	(1.103)
	T-UL-5	0.035	-65	139.2	18.8*	7,410	.870	1.106
	T-UL-6	0.037	-65	174.1	---	---	1.088	---
	Avg			(156.7)			(.979)	(1.106)
$[90]_{6T}$ Transverse tension coupon 6 plies	T-UT-1	0.036	RT	3.54	1.72*	2,060	Premature failure	
	T-UT-2	0.037	RT	1.82	---	---		
	T-UT-3	0.036	350	0.98	1.11*	1,050		
	T-UT-4	0.036	350	2.07	0.97**	2,140		
	T-UT-5	0.035	-65	5.02	---	---		
	T-UT-6	0.035	-65	---	---	---		

*Extensometer data
**Strain gage data
***Predicted value (Refer to section V.)

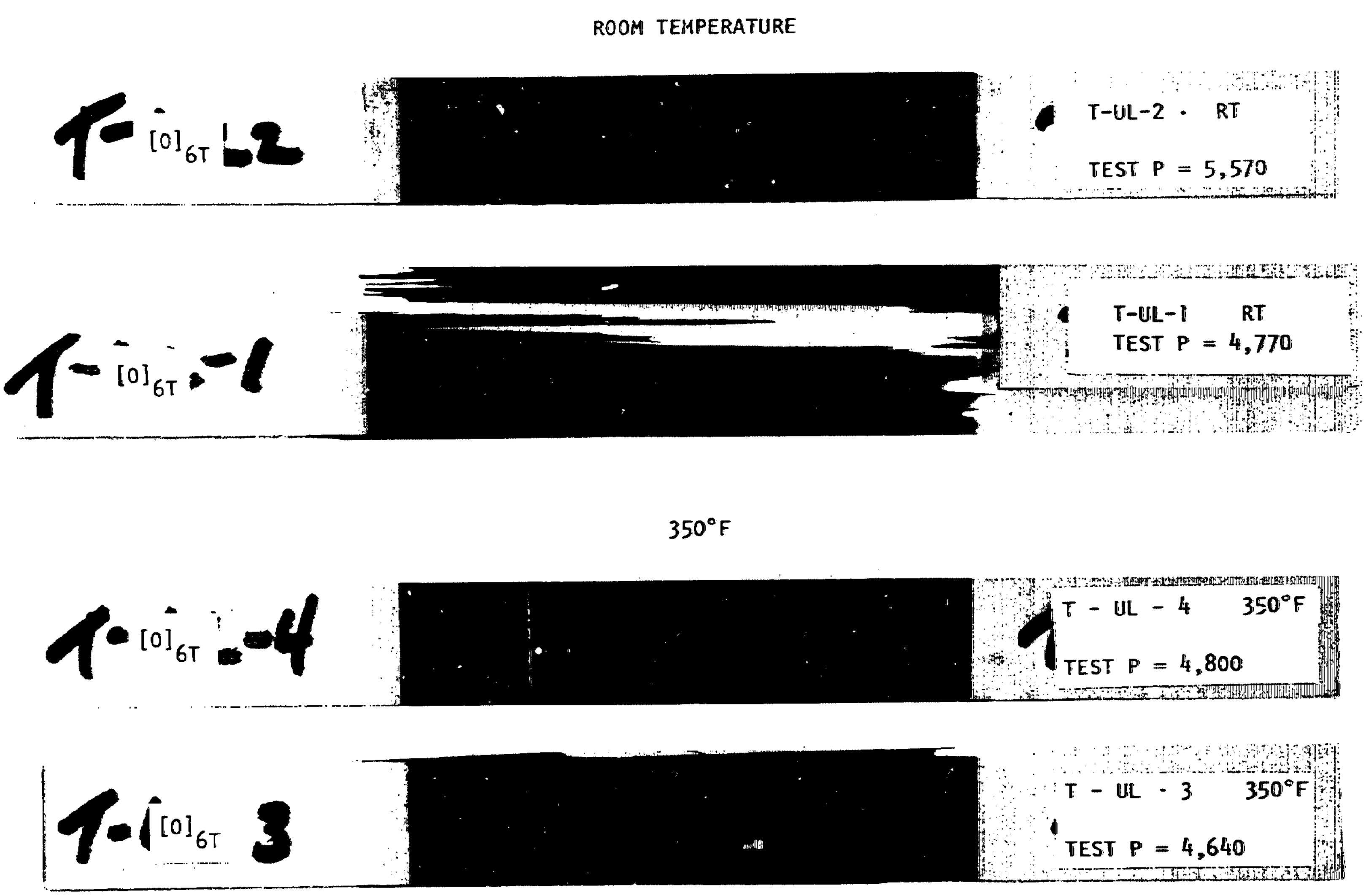
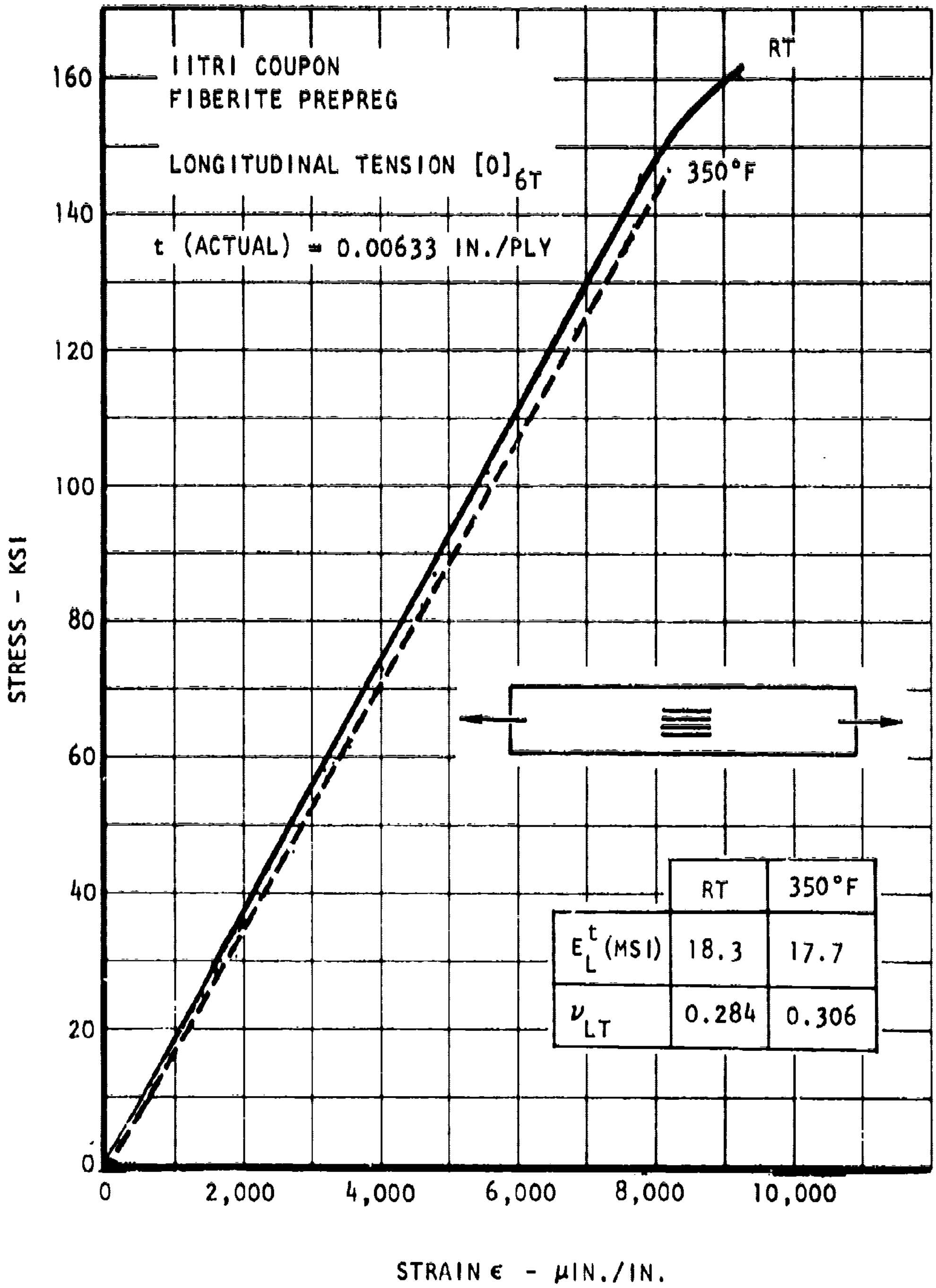


Figure 37. Failed Unidirectional $[0]_6$ Tension Specimens - Graphite/Epoxy Type A/3002 Batch - Untreated Fiber - Room Temperature and 350°F



	RT	350°F
E_L^t (MSI)	18.3	17.7
ν_{LT}	0.284	0.306

Figure 38. Graphite/Epoxy - Typical Unidirectional Tension - Stress-Strain Properties - Type A/3002 Batch - Untreated Fiber

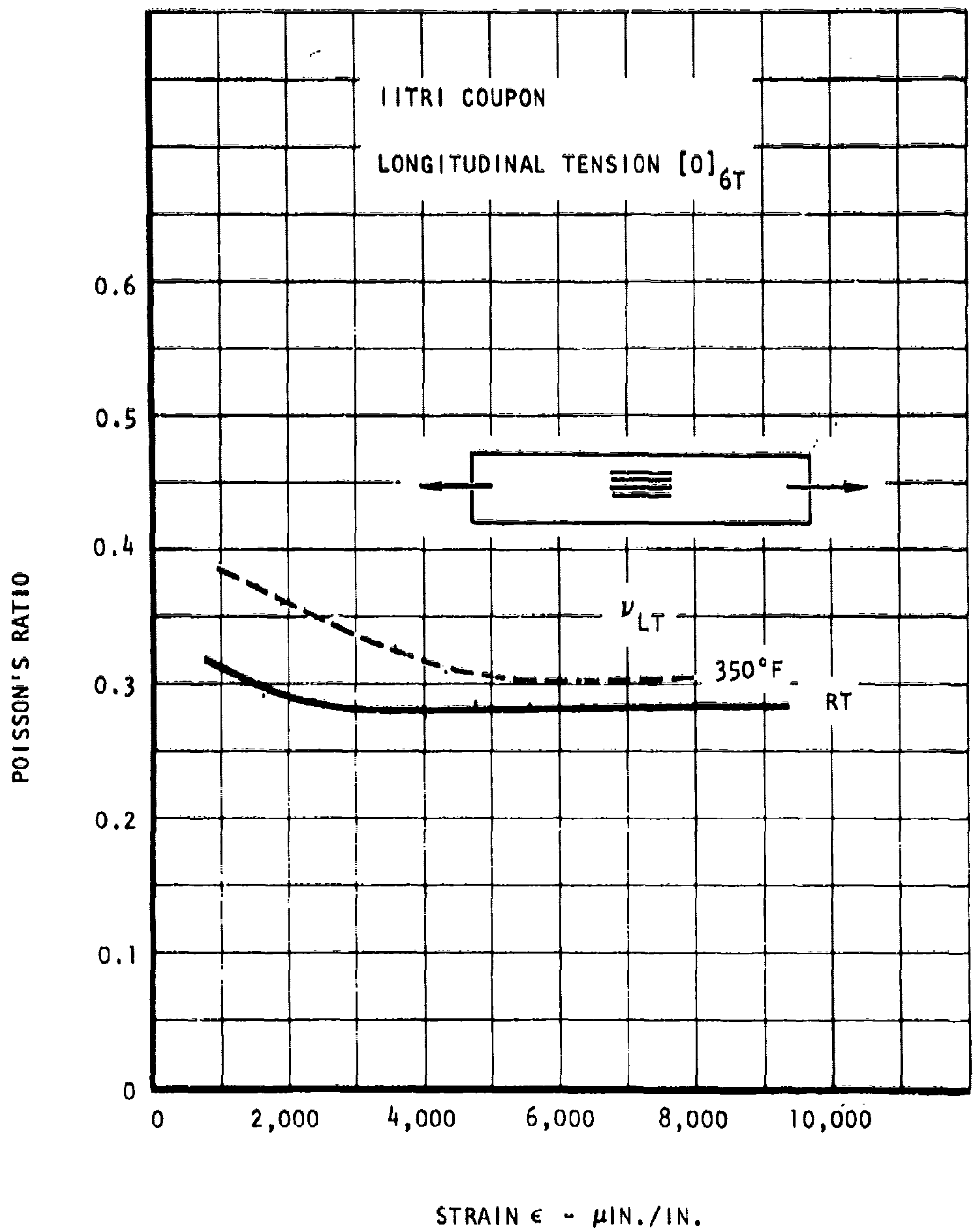


Figure 39. Graphite/Epoxy - Typical Poisson's Ratios Versus Strain - Unidirectional - Type A/3002 Batch - Untreated Fiber

Compression Properties

Treated Graphite Fiber Laminates (Type AS/3002)

Tables XI and XII present longitudinal and transverse compression data for unidirectional Type AS/3002 batch graphite/epoxy laminates. Both sandwich bending beam and edgewise compression tests were run, using three temperatures: -65°F, room temperature, and 350°F. The longitudinal compression strengths and modulus values were in good agreement with predicted values, while the transverse compression strengths and moduli were 25 to 137 percent higher than expected. The sandwich bending beam specimen had graphite/epoxy face sheets which were secondarily bonded to the core. Figures 40, 41, 42, and 43 show photographs of typical failed specimens, and figures 30, 31, and 32 (presented in the unidirectional tension section) present typical compression stress-strain curves for -65°F, room temperature, and 350°F. Furthermore, typical transverse compression stress-strain curves for continuous-type AS/3002 graphite/epoxy unidirectional laminates are presented in figure 44. In general, the continuous material appears to have strength and modulus values comparable to that of the batch material, as is expected.

Untreated Graphite Fiber Laminates (Type A/3002)

Unidirectional laminate compression data for Type A/3002 batch untreated graphite/epoxy material are presented in table XIII. The bending beam specimen yielded strength and modulus values about as predicted, while the edgewise compression specimens failed prematurely, probably because of a fabrication problem. A typical stress-strain curve is included in figure 45.

TABLE XI. UNIDIRECTIONAL GRAPHITE/EPOXY LONGITUDINAL COMPRESSION DATA (TYPE AS/3002 BATCH)

Orientation	Specimen No.	Thickness (in.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus (Msi)	Ultimate Strain (μ in./in.)	Test/Predicted	
							Strength	Modulus
$[0]_{6T}$ Longitudinal compression sandwich bending beam**	CLBB-UL11	0.036*	-65	174.10	No data	No data	1.09	No data
	CLBB-UL12	0.036*	-65	176.50	No data	No data	1.10	No data
	CLBB-UL13	0.036*	-65	193.10	No data	No data	1.21	No data
	CLBB-UL14	0.036*	-65	196.40	No data	No data	1.23	No data
	CLBB-UL15	0.036*	-65	191.90	No data	No data	1.20	No data
	Avg			(186.40)			(1.17)	
6 plies	CLBB-UL1	0.036*	RT	177.9	16.0	-13,684 SG	1.11	0.94
	CLBB-UL2	0.036*	RT	170.99	16.0	No data	1.07	0.94
	CLBB-UL3	0.036*	RT	169.78	16.0	No data	1.06	No data
	CLBB-UL4	0.036*	RT	168.10	No data	No data	1.05	No data
	CLBB-UL5	0.036*	RT	168.70	No data	No data	1.05	No data
	Avg			(171.09)	(16.0)	(-13,684)	(1.07)	(0.94)
	CLBB-UL6	0.036*	350	60.40	No data	No data	0.93	No data
	CLBB-UL7	0.036*	350	61.11	No data	No data	0.94	No data
	CLBB-UL8	0.036*	350	60.27	No data	No data	0.93	No data
	CLBB-UL9	0.036*	350	86.09	No data	No data	1.33	No data
	CLBB-UL10	0.036*	350	65.03	15.66	-4,310 SG	1.00	0.98
	TLBB-UL18	0.036*	350	77.34	No data	No data	1.19	No data
	Avg			(68.37)	(15.66)	(-4,310)	(1.05)	(0.98)

* Nominal face sheet thickness

** Sandwich beam with one face sheet of steel and one face sheet of secondary bonded graphite/epoxy (adhesive: Metlbond 329-7)

NOTE TLBB-UL18 was intended to be tested as a longitudinal tension sandwich bending beam, but was mistakenly tested in compression.

TABLE XII. UNIDIRECTIONAL GRAPHITE/EPOXY TRANSVERSE COMPRESSION DATA (TYPE AS/3002 BATCH)

Test Orientation	Specimen No.	Thickness (in.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus (Msi)	Ultimate Strain (μ in./in.)	Test/Predicted	
							Strength	Modulus
$[90]_{6T}$ Transverse edgewise compression sandwich specimen	EC-UT-6	0.036*	-65	49.1	4.02	-16,072	1.96	2.37
	EC-UT-7	0.036*	-65	43.9	4.11	-15,682	1.76	2.42
	EC-UT-8	0.036*	-65	28.3	4.31	-7,504	1.13	2.54
	EC-UT-12	0.036*	-65	27.3	3.67	-10,960	1.09	2.16
	Avg			(37.15)	(4.03)	(-12,555)	(1.49)	(2.37)
6 plies	EC-UT-1	0.036*	RT	25.06	2.80	-9,954 SG	1.09	1.65
	EC-UT-2	0.036*	RT	24.5	3.86	-7,433	0.98	2.27
	EC-UT-9	0.036*	RT	40.1	3.52	-14,530	1.60	2.07
	EC-UT-13	0.036*	RT	27.76	4.49	-8,143	1.11	2.64
	EC-UT-14	0.036*	RT	39.16	3.90	-14,476	1.57	2.29
	Avg			(31.32)	(3.71)	(-10,907)	(1.25)	(2.18)
	EC-UT-3	0.036*	350	21.70	1.78	-18,462 SG	3.34	1.98
	EC-UT-4	0.036*	350	17.40	1.78	-19,974	2.68	1.98
	EC-UT-5	0.036*	350	17.50	1.99	-17,230	2.69	2.21
	EC-UT-10	0.036*	350	19.50	1.83	-20,440	3.00	2.03
	EC-UT-11	0.036*	350	19.10	1.71	---	2.94	1.90
	Avg			(19.04)	(1.82)	(-19,027)	(2.93)	(2.02)
$[90]_{6T}$ Transverse compression sandwich bending beam** 6 plies	CLBB-UT1	0.036	RT	56.8	3.1	-13,911 SG	2.27	1.82

* Nominal face sheet thickness

** Sandwich beam with one face sheet of steel and one of secondary bonded graphite/epoxy (adhesive: Metlbond 329-7)

NOTE SG = Strain gage value; all others are extensometer values.

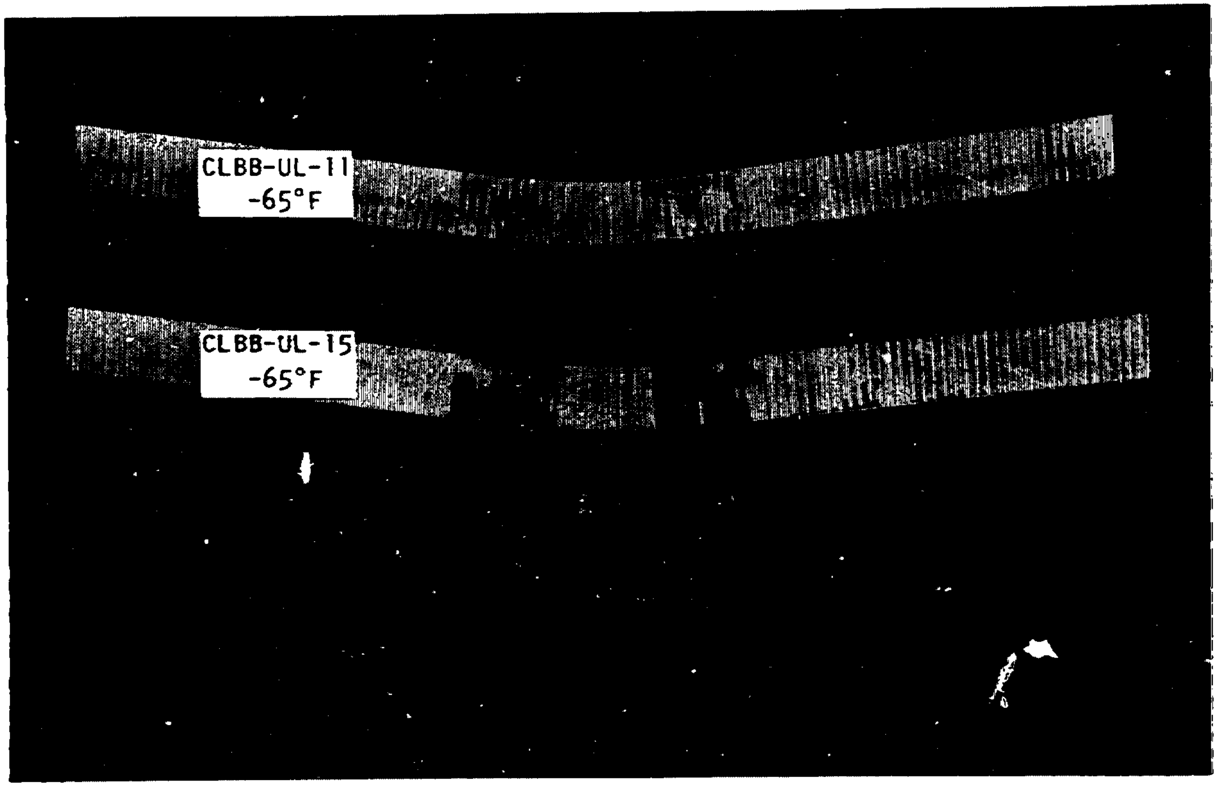


Figure 40. Unidirectional Compression Sandwich Bending Beams, Type AS/3002 - Batch Graphite/Epoxy, -65°F

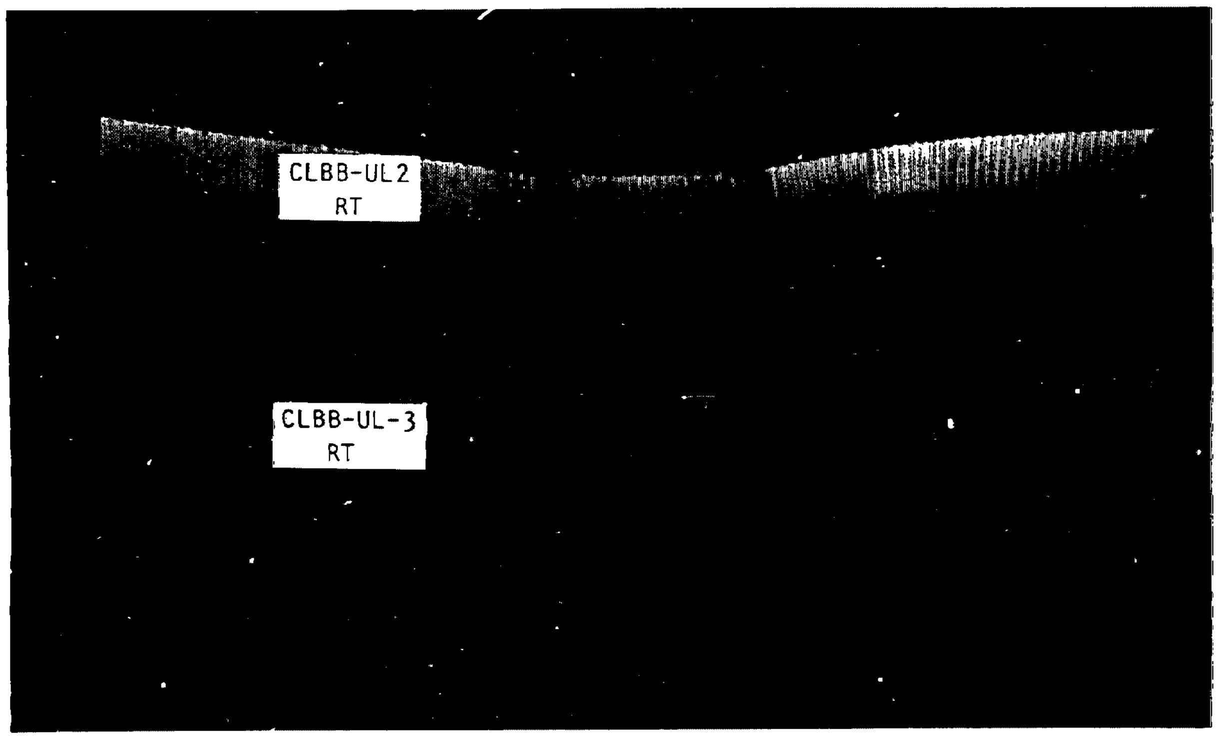


Figure 41. Unidirectional Compression Sandwich Bending Beams, Type AS/3002 - Batch Graphite/Epoxy, Room Temperature

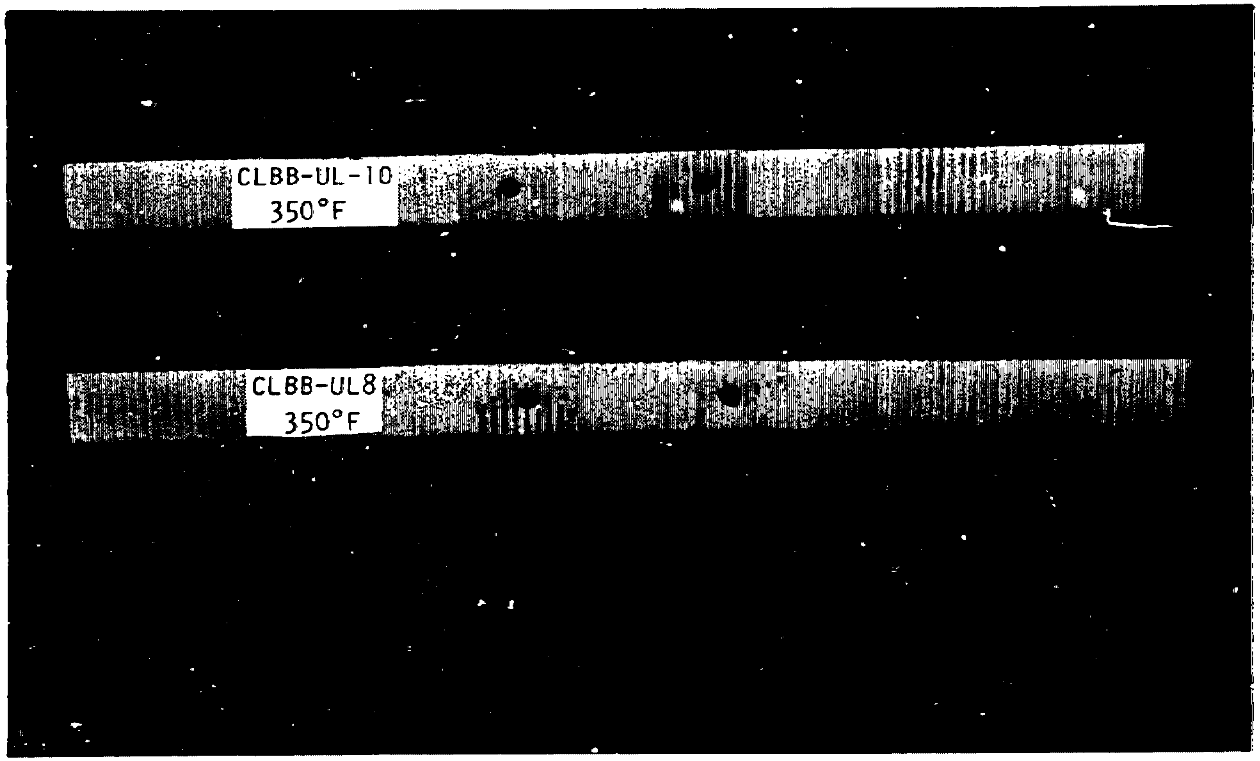


Figure 42. Unidirectional Compression Sandwich Bending Beams, Type AS/3002 - Batch Graphite/Epoxy, 350°F

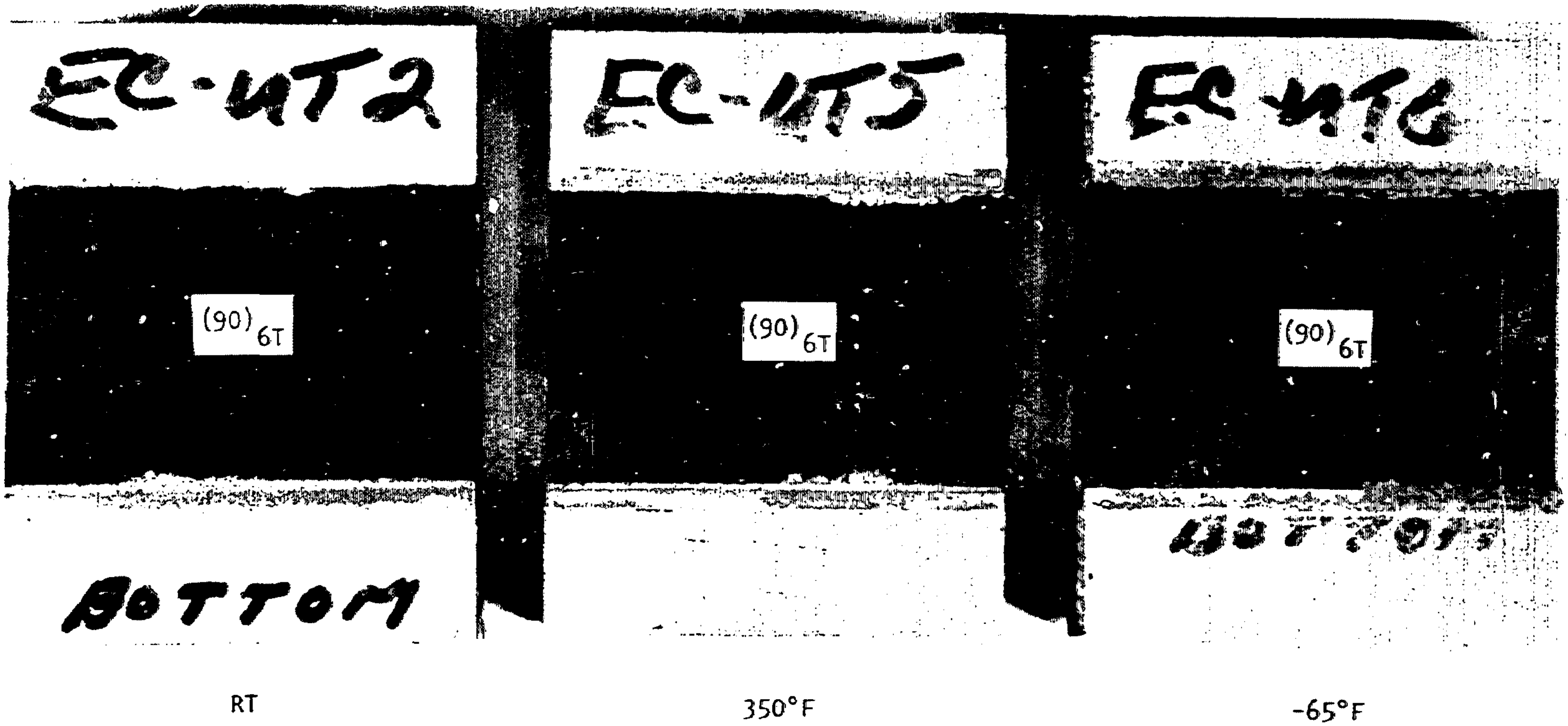
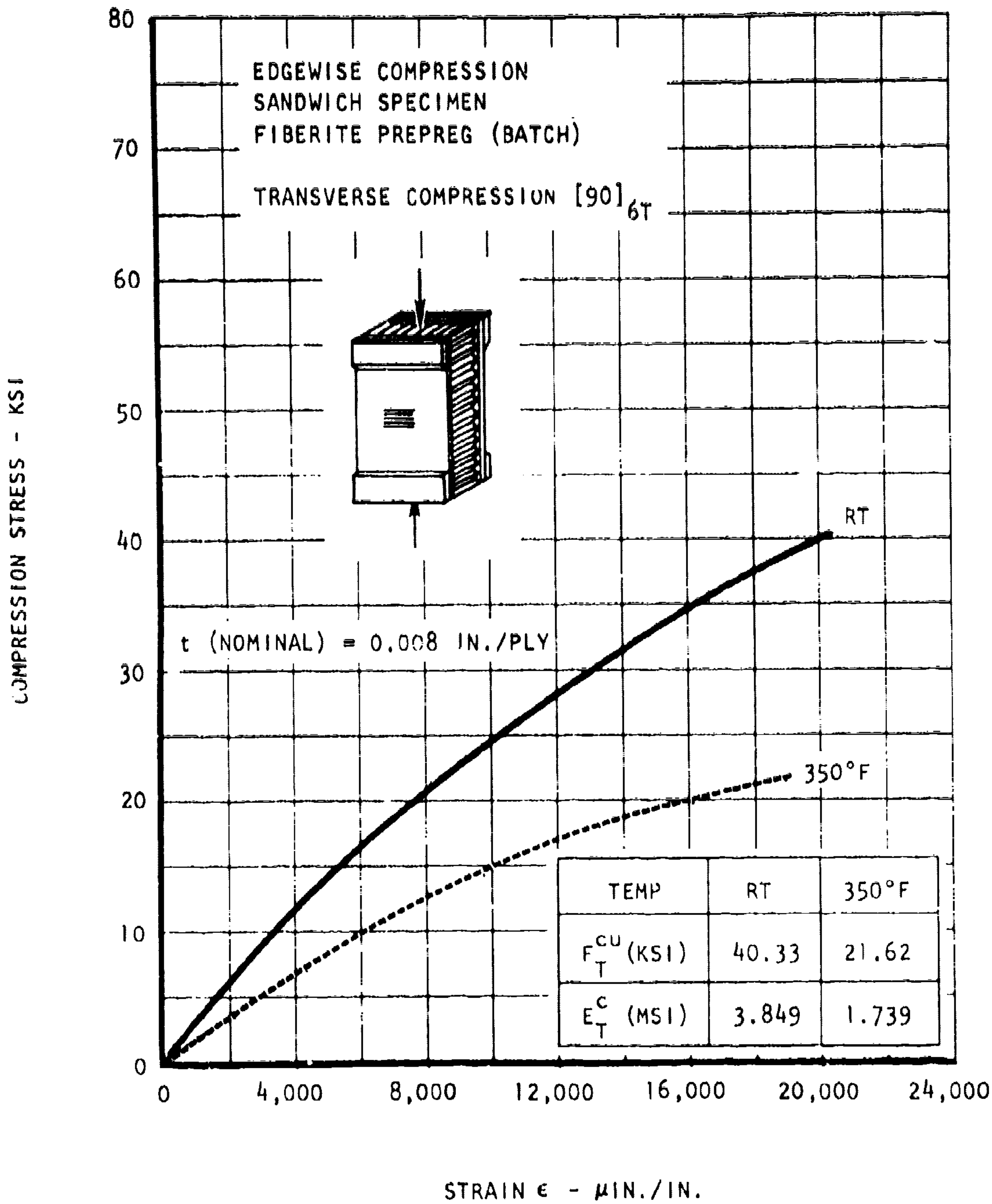


Figure 43. Typical Failed Edgewise Compression Sandwich Specimens - Unidirectional Graphite/Epoxy - Type AS/3002 - Batch, [90] Orientation, RT, 350°F, and -65°F



TEMP	RT	350°F
F_T^{cu} (KSI)	40.33	21.62
E_T^c (MSI)	3.849	1.739

Figure 44. Graphite/Epoxy Typical Edgewise Compression Sandwich Stress-Strain Properties - Transverse Unidirectional - Type AS/3002 - Continuous-Treated Fiber

TABLE XIII. UNIDIRECTIONAL GRAPHITE/EPOXY COMPRESSION DATA (TYPE A/3002 BATCH - UNTREATED FIBER)

Test Orientation	Specimen No.	Thickness (in.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus (Msi)	Ultimate Strain (μ in./in.)	Test/Predicted*** Strength	Test/Predicted*** Modulus
$[0]_{6T}$ Longitudinal compression sandwich beam** 6 plies	CLB-UL-1	0.036*	RT	227.8	16.3	14,500	1.424	0.959
$[0]_{6T}$ Longitudinal edgewise compression sandwich 6 plies	EC-UL-2	0.036*	RT	105.1	---	Premature failure		
	EC-UL-3	0.036*	RT	112.0	---	Premature failure		
	Avg			(108.6)				

* Nominal face sheet thickness

** Sandwich beam with one face sheet of steel and one face sheet of secondary bonded graphite/epoxy (adhesive: Metlbond 329-7)

*** Predicted value (refer to section V).

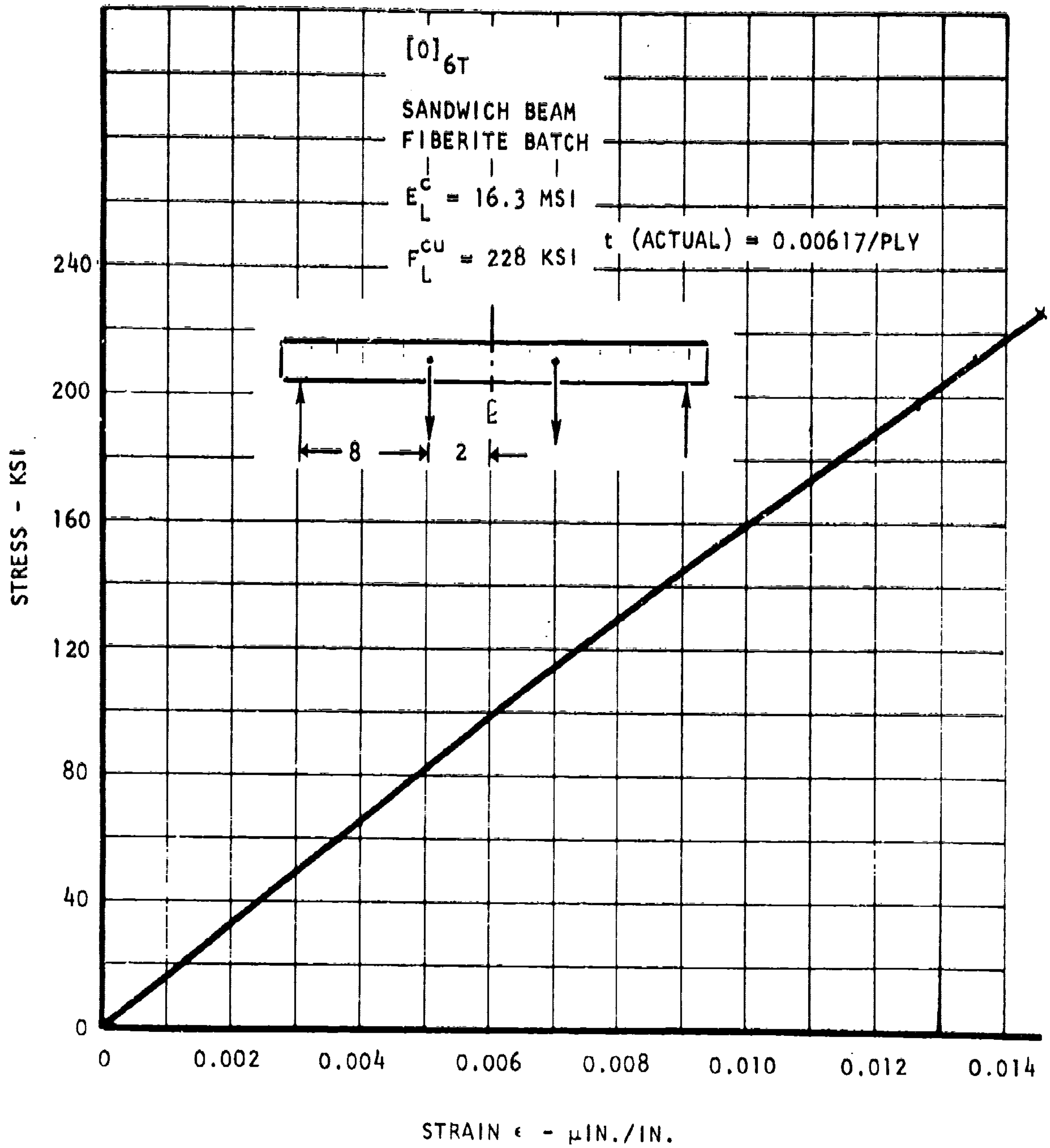


Figure 45. Graphite/Epoxy - Typical Unidirectional Compression Stress-Strain Properties - Type A/3002 Batch - Untreated Fiber

In-Plane Shear Properties

In-plane shear data for both Type AS/3002 (treated) and Type A/3002 (untreated) batch unidirectional graphite/epoxy laminates at -65°F, room temperature, and 350°F are presented in table XIV. The data were obtained by use of rail shear type test specimens as shown in figures 46 and 47, and typical specimen failure modes are pictured in figures 48 and 49. Note that the failures were a longitudinal splitting along the fiber direction, as is expected.

In general, the modulus values obtained compared well with predicted values while the strength values were, for the most part, lower than predicted, with the untreated material appearing to have the lowest strength. These low-strength values might be due in part to the rail shear test method.

Typical shear stress-strain curves are presented in figures 50, 51, and 52.

Examination of figures 50, 51, and 52 indicates that the unidirectional shear stress-strain curves are not indicative of the total strain capacity of the graphite/epoxy laminate. Using the procedures outlined in reference 7, the total room temperature and 350°F shear stress-strain curves for unidirectional laminate using [±45] crossply tension coupon data were computed, as shown in figure 53. The test data from unidirectional tension coupons in the longitudinal (0°) and transverse (90°) directions are also required.

TABLE XIV. UNIDIRECTIONAL GRAPHITE/EPOXY IN-PLANE SHEAR DATA (TYPE AS/3002 AND TYPE A/3002 BATCH)

Test Orientation	Specimen No.	Thickness (in.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus (Msi)	Ultimate Strain (μ in./in.)	Test/Predicted	
							Strength	Modulus
$[0]_{6T}$	RS-UL-6	0.036	-65	3.38	No data	No data***	0.38	No data
Rail	RS-UL-12	0.036	-65	3.08	No data	No data	0.31	No data
shear	RS-UL-13	0.036	-65	1.77	No data	No data	0.18	No data
specimen	RS-UL-14	0.036	-65	4.28	No data	No data	0.43	
	Avg			(3.24)			(0.32)	
6 plies								
	RS-UL-1	0.036	RT	4.42	No data	No data***	0.44	No data
	RS-UL-2	0.036	RT	5.40	0.870	6,900 SG***	0.54	1.34
	RS-UL-7	0.036	RT	9.72	No data	No data	0.97	No data
	RS-UL-8	0.036	RT	2.73	0.750	2,497 SG	0.27	1.15
	RS-UL-16	0.036	RT	7.69	0.860	10,909 SG	0.77	1.32
	Avg			(5.99)	(0.830)	(6,769)	(0.60)	(1.27)
	RS-UL-3	0.036	350	.44	No data	No data***	0.11	No data
	RS-UL-5	0.036	350	2.75	No data	No data***	0.69	No data
	RS-UL-9	0.036	350	4.39	0.35	77,000* SG	1.10	1.00
	RS-UL-10	0.036	350	4.39	No data	No data	1.10	No data
	RS-UL-11	0.036	350	3.89	No data	No data	0.97	No data
	Avg			(4.22)**	(0.35)	(77,000)	(0.82)	(1.00)

* Estimated ultimate strain

** Average of three Type AS/3002 tests

*** Untreated

NOTE SG = estimated ultimate strain (strain gage data)

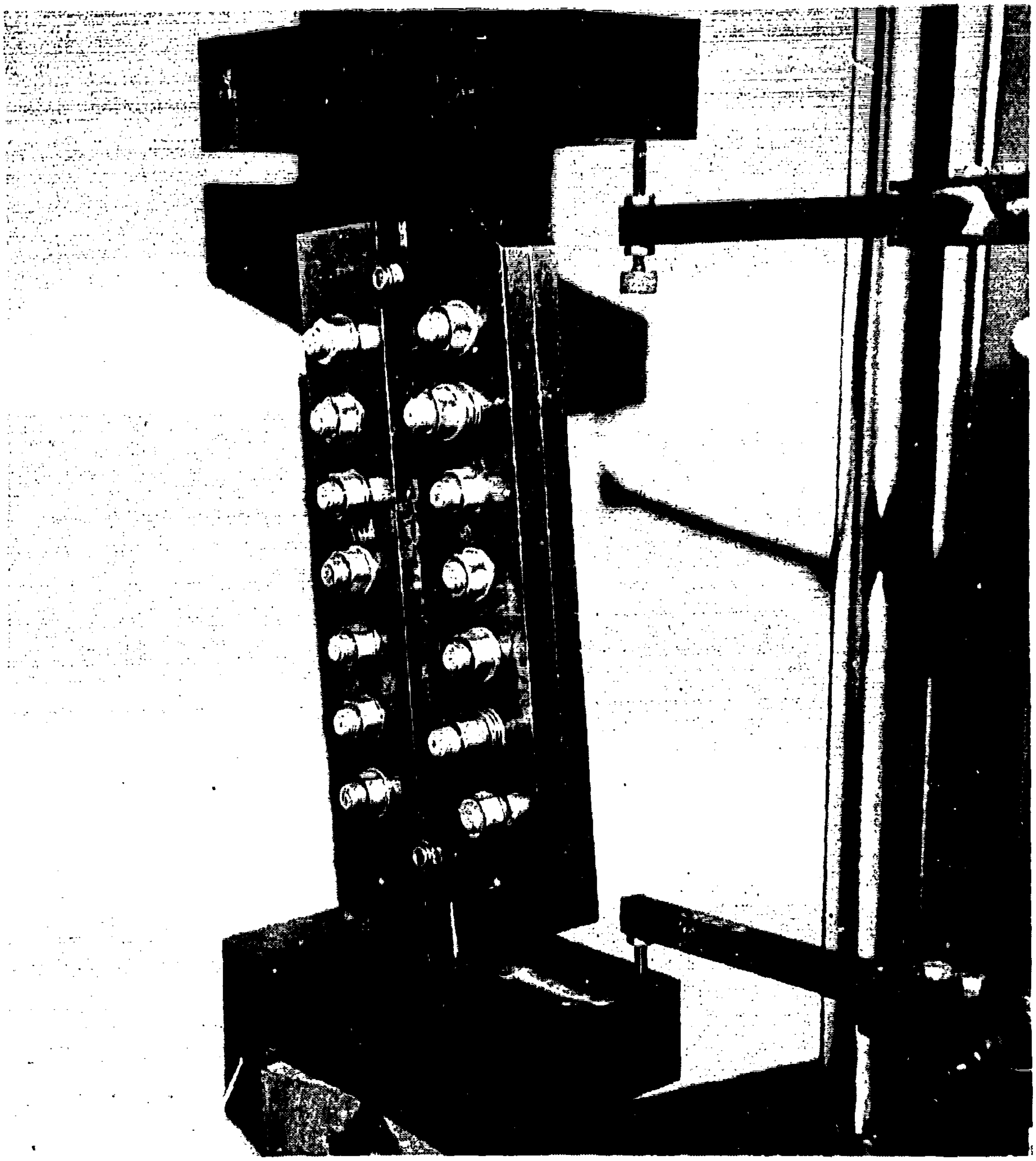


Figure 46. Rail Shear Test Fixture and Test Setup

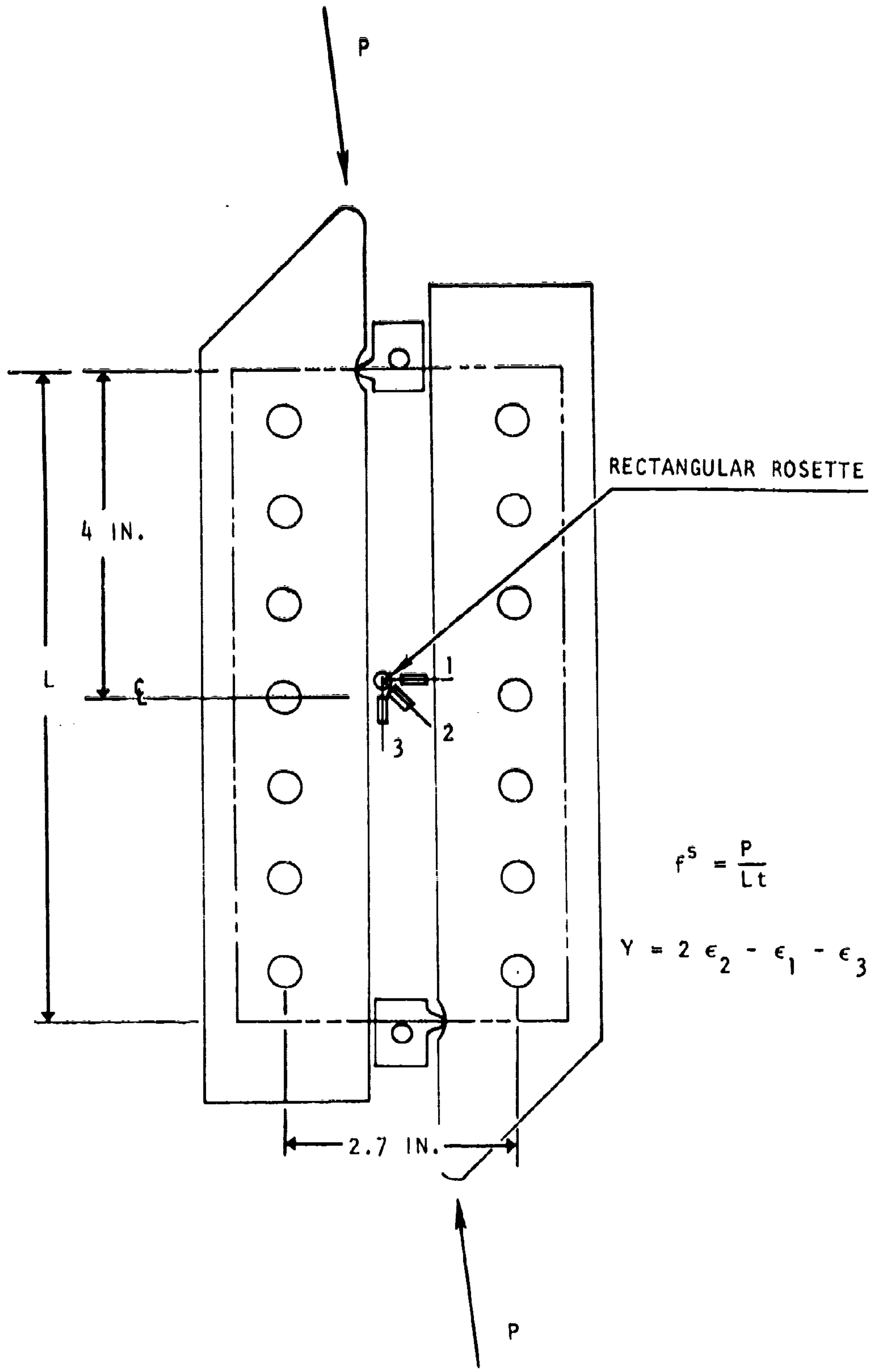


Figure 47. Rail Shear Test Setup and Instrumentation

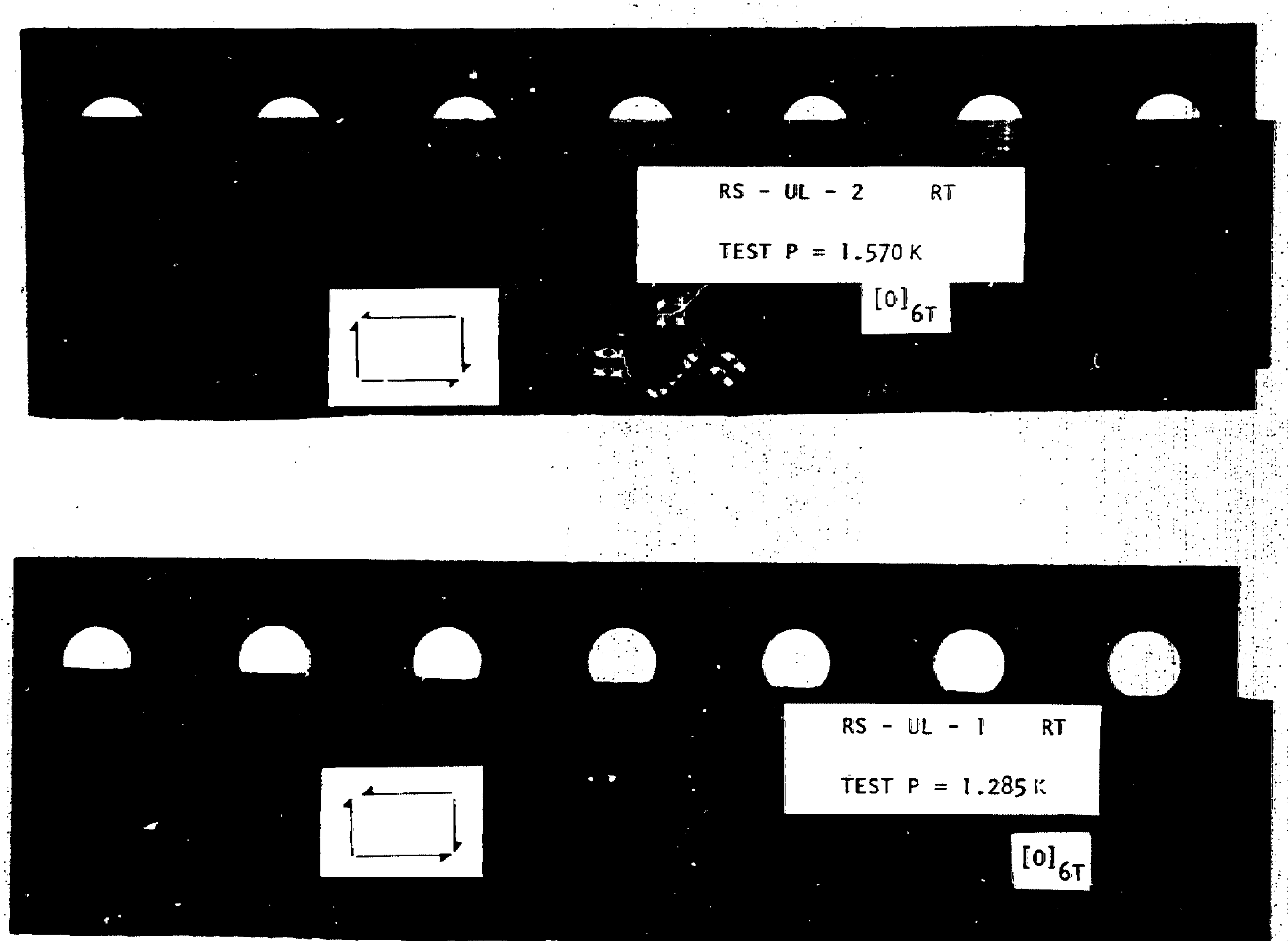


Figure 48. Failed Rail Shear Specimens - $[0]_6$ - Room Temperature Set

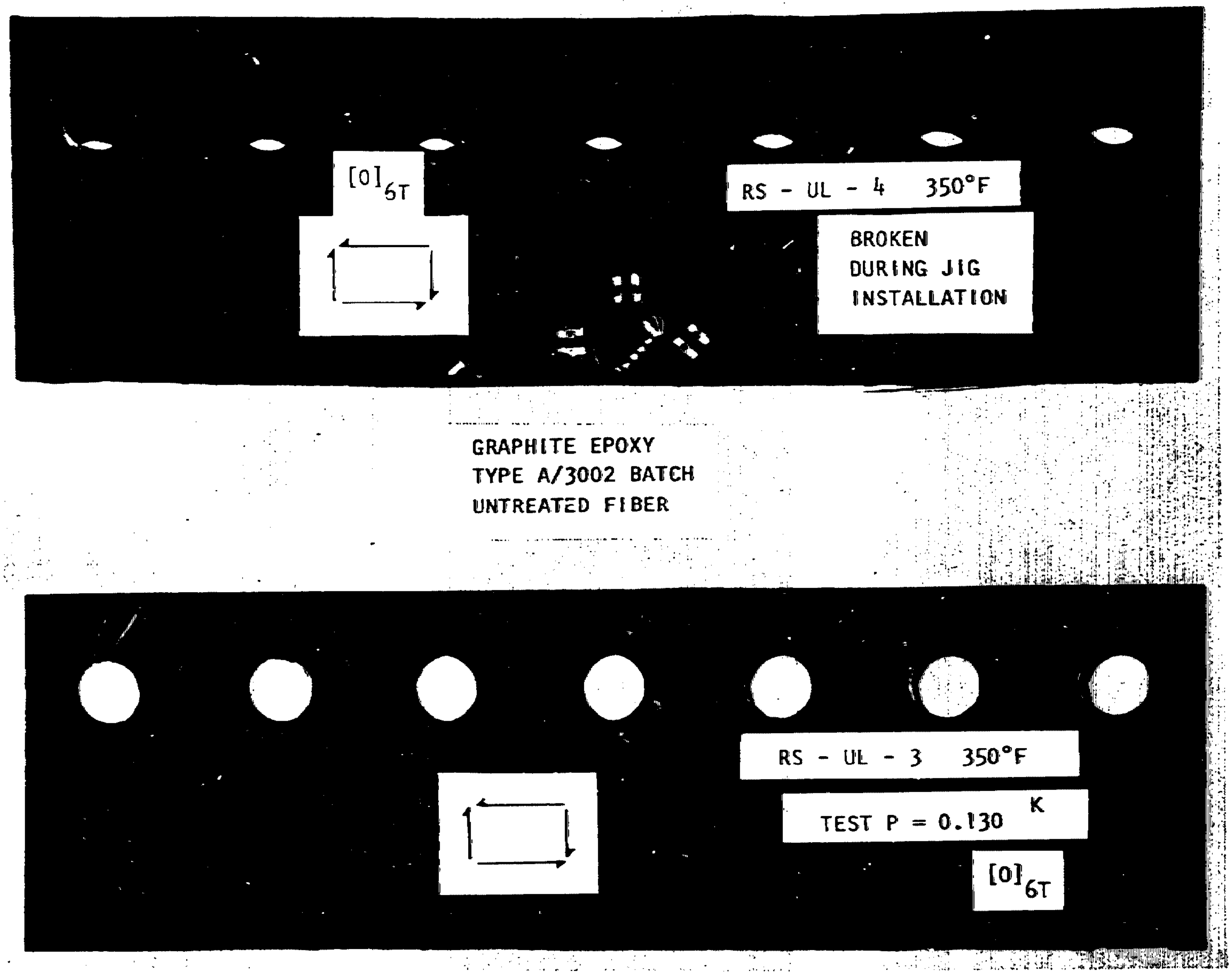


Figure 49. Failed Rail Shear Specimens - $[0]_6$ - Elevated Temperature Test 350°F

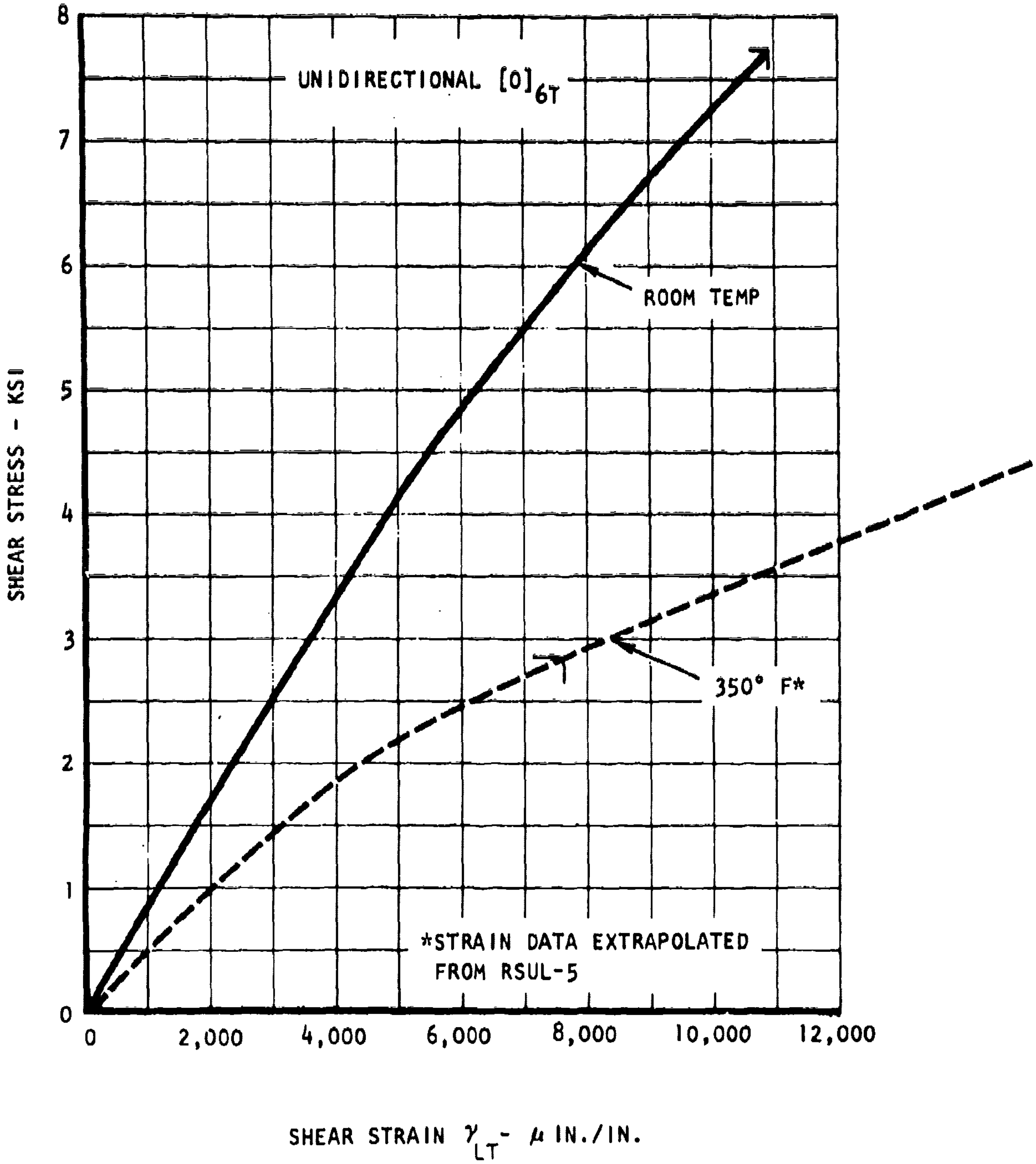


Figure 50. Unidirectional Graphite/Epoxy Typical Shear Stress-Strain Curves, Type AS/3002 - Batch, Room Temperature and 350° F

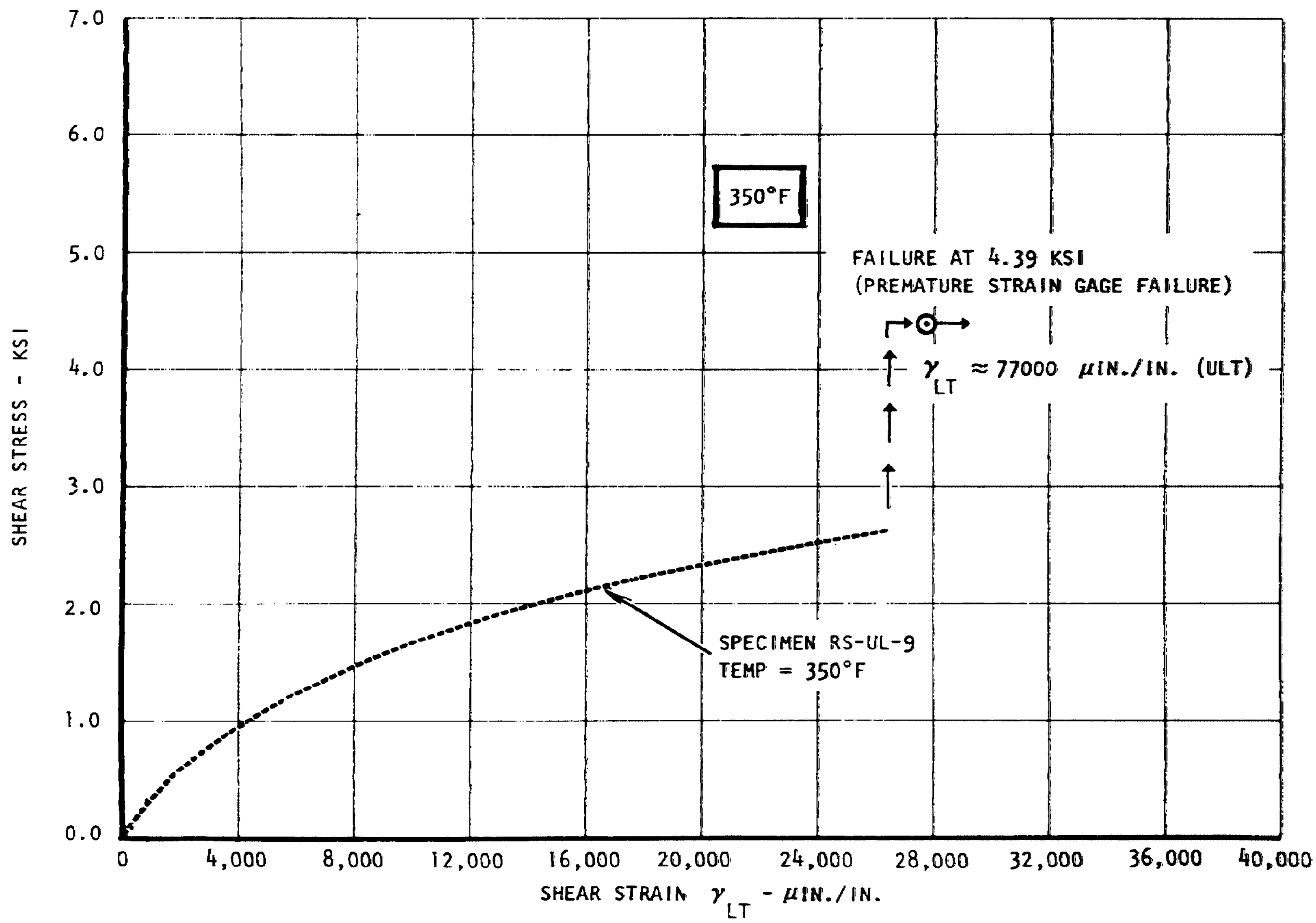


Figure 51. Unidirectional Graphite/Epoxy Laminate - Rail Shear Stress-Strain Curve at 350° F (Type AS/3002 - Batch) Treated Fiber

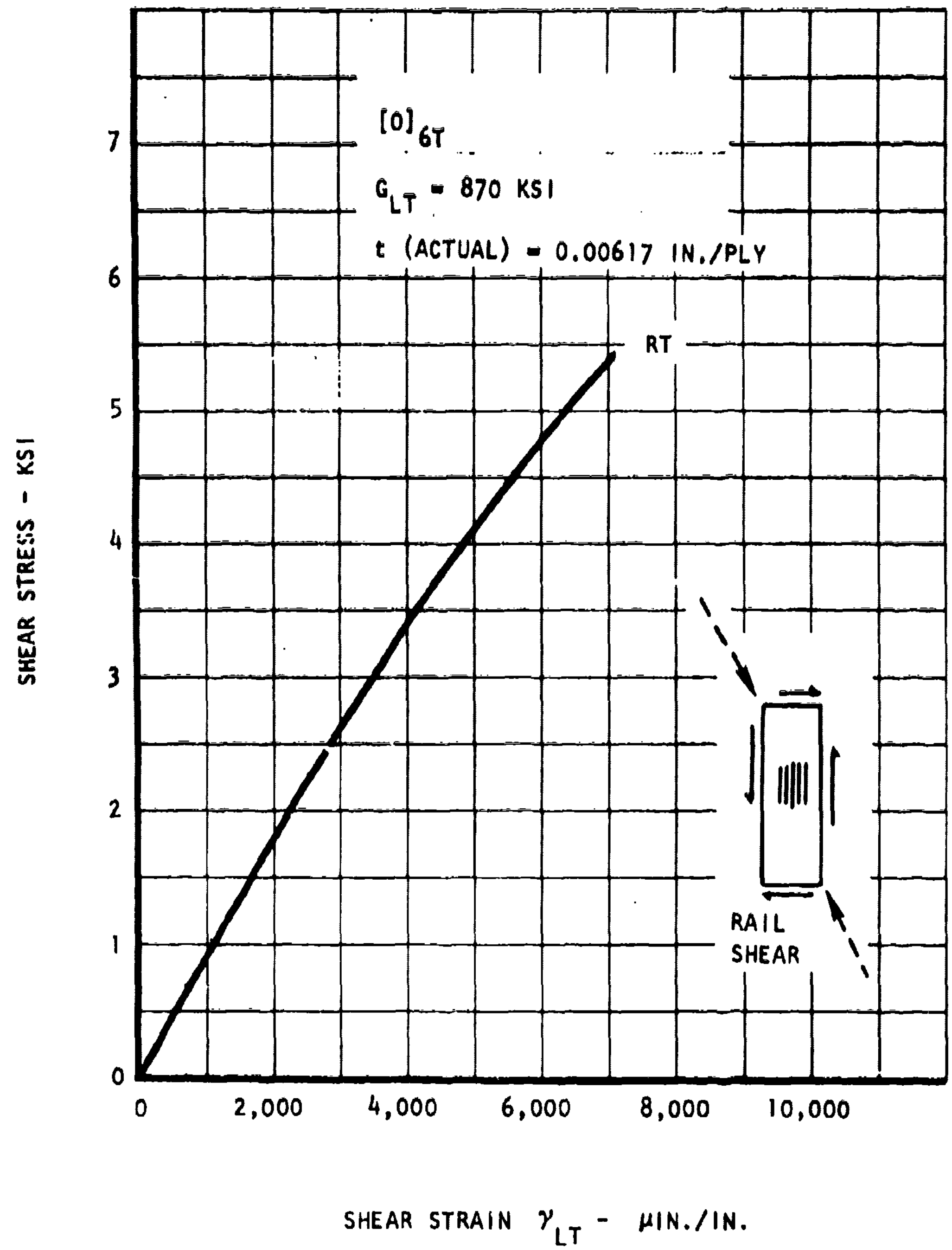


Figure 52. Graphite/Epoxy - Typical In-Plane Shear Stress-Strain Properties - Unidirectional - Type A/3002 Batch - Untreated Fiber

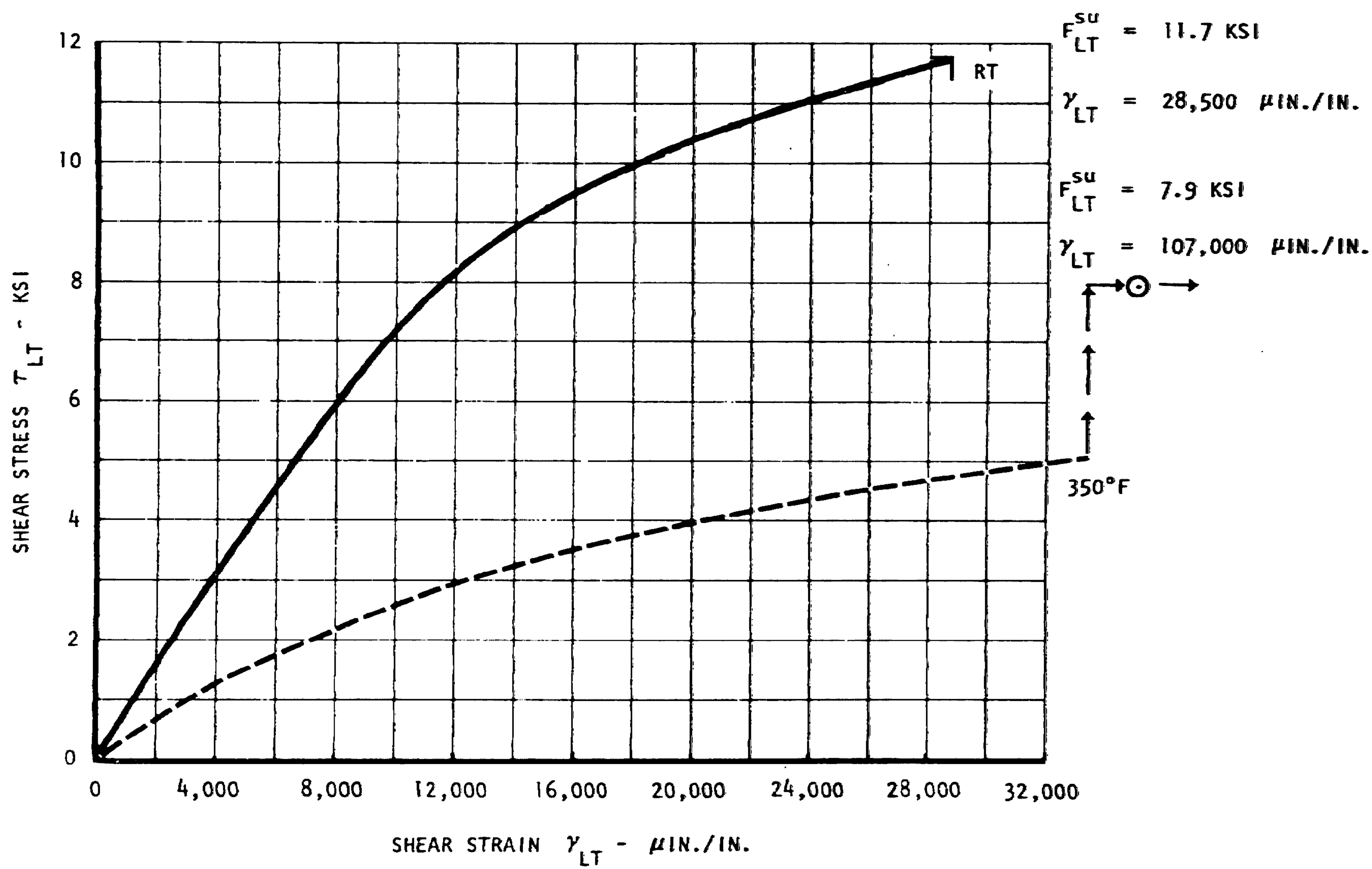


Figure 53. Calculated Unidirectional Shear Stress-Strain Curves at Room Temperature and 350° F - Type AS/3002 Graphite/Epoxy

The detailed procedure for the room temperature case is as follows:

1. By testing unidirectional laminate in the 0° and 90° directions in uniaxial tension, the values E_L, E_T, and ν_{LT} are determined (see figure 54.) Then ν_{TL} is obtained by the relation:

$$\nu_{TL} = \nu_{LT}\, E_T/E_L$$

2. The material constant U_1 is determined from:

$$U_1 = \left(E_L + E_T + 2\nu_{LT} E_T\right)/\left[8\left(1 - \nu_{LT}\nu_{TL}\right)\right]$$

3. By testing the ±45° laminate in tension, one obtains the ±45° Poisson's ratio, $\nu_{xy} = \epsilon_y/\epsilon_x$ and tension modulus, $E'_x = \dfrac{\partial\sigma_x}{\partial\epsilon_x}$ (tangent modulus). (See figures 54 and 55.)

4. The shear strain, γ_{LT}, is related to the ±45° tension strain by the expression:

$$\gamma_{LT} = (1 + \nu_{xy})\, \epsilon_x$$

5. The shear modulus, G'_{LT}, is determined from:

$$G'_{LT} = 2U_1\, E'_x/(8U_1 - E'_x)$$

6. The shear stress, τ_{LT}, is then obtained from:

$$\tau_{LT} = G'_{LT}\, \gamma_{LT}$$

Note that, because shear-strain values beyond the elastic (linear) range are needed, γ_{LT} is incremented. Therefore,

7. $$\Delta\tau_{LT} = G'_{LT}\Delta\gamma_{LT}$$

The $\Delta\tau_{LT}$ values must be summed in order to obtain τ_{LT}.

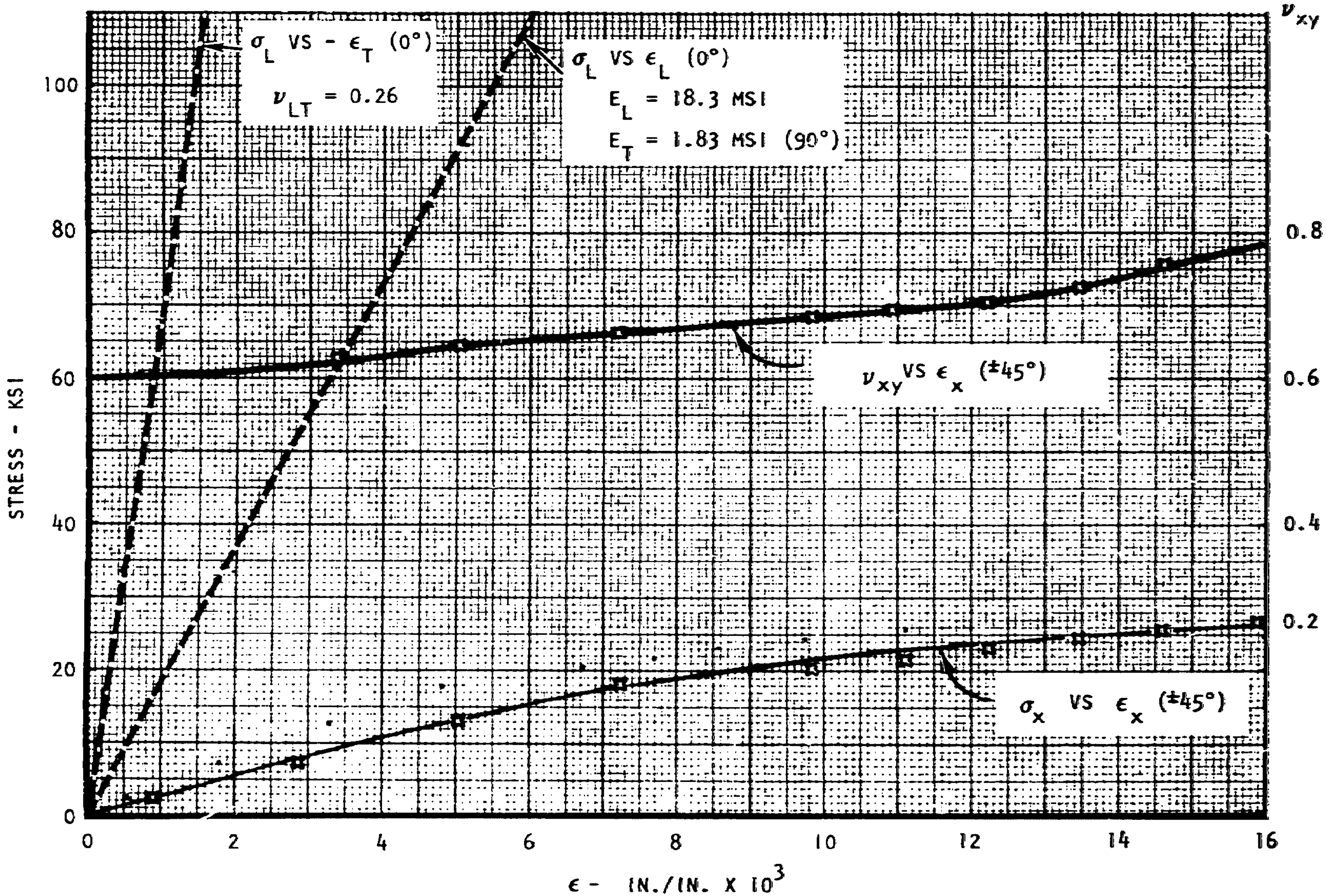


Figure 54. Tension Coupon Data, $[\pm 45]_{2S}$ Crossply and $[0]_{6T}$ Unidirectional Laminates - Type AS/3002 - Graphite/Epoxy - Room Temperature

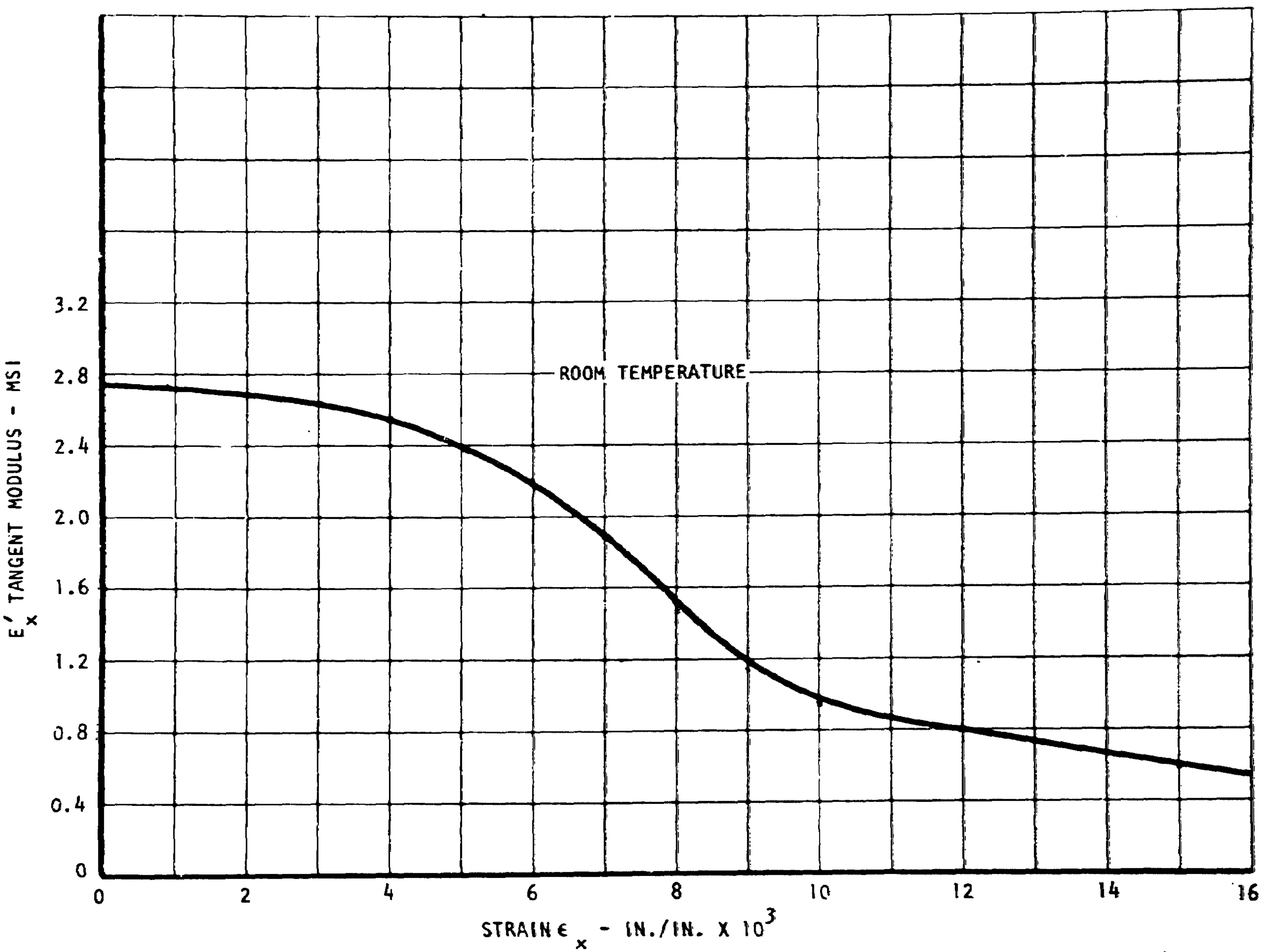
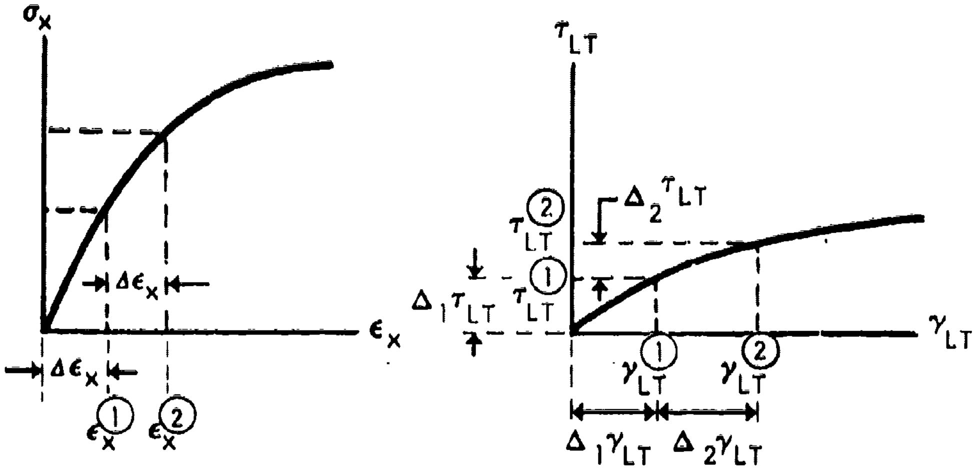


Figure 55. [$\pm$45] Tension Coupon - Tangent Modulus Versus Strain - Graphite/Epoxy Type AS/3002

8. The procedure is:

a. Obtain E_L, E_T; ν_{LT}, ν_{TL}, and calculate U_1

b. Obtain σ_x versus ϵ_x of ±45° laminate.



c. Calculate E_x' and ν_{xy} for initial $\Delta\epsilon_x$.

d. Calculate $\gamma_{LT}^{(1)}$, G_{LT}', and $\Delta_1\tau_{LT}$ for $\epsilon_x^{(1)}$, plot $\gamma_{LT}^{(1)}$, $\tau_{LT}^{(1)}$.

e. Calculate $\gamma_{LT}^{(2)} = \epsilon_x^{(2)}\left(1 + \nu_{xy}\right)$

f. Calculate E_x' and ν_{xy} for the range of $\epsilon_x^{(1)}$ to $\epsilon_x^{(2)}$.

g. Calculate $\Delta_2\,\gamma_{LT}$, G_{LT}', and $\Delta_2\,\tau_{LT} = G_{LT}'\Delta_2\gamma_{LT}$.

h. Calculate $\tau_{LT}^{(2)} = \tau_{LT}^{(1)} + \Delta_2\,\tau_{LT}$, plot $\tau_{LT}^{(2)}$, $\gamma_{LT}^{(2)}$.

i. Repeat steps e. through h.

A simple computer program was written to generate the data for the curves shown in figure 53. The typical room temperature input and output data are shown as follows:

GRAPHITE/EPOXY TYPE AS/3C02 ROOM TEMP. INPUT DATA

EL= 18.3 ET= 1.8 VLT= 0.260 ← UNIDIRECTIONAL DATA

STRESS(X) (PSI) σ_x	STRAIN(X) (MICRO IN/IN) ϵ_x	STRAIN(Y) (MICRO IN/IN) ϵ_y	POISSONS RATIO ν_{xy}	MODULUS(EX) (MSI) E_x'
0.	0.	0.	0.600	2.800
2750.	1000.	-602.	0.602	2.750
5600.	2000.	-1220.	0.610	2.690
8200.	3000.	-1860.	0.620	2.640
10800.	4000.	-2520.	0.630	2.550
13000.	5000.	-3200.	0.640	2.400
15400.	6000.	-3900.	0.650	2.180
17500.	7000.	-4620.	0.660	1.890
19000.	8000.	-5320.	0.665	1.520
20300.	9000.	-6057.	0.673	1.190
21800.	10000.	-6820.	0.682	0.970
23700.	12000.	-8400.	0.700	0.800
26100.	14000.	-10290.	0.735	0.670
26300.	16000.	-12480.	0.780	0.560

[±45] TENSION COUPON DATA

GRAPHITE/EPOXY TYPE AS/3002 ROOM TEMP. OUTPUT DATA

SHEAR STRESS(LT) (PSI) τ_{LT}	SHEAR STRAIN(LT) (MICRO IN/IN) γ_{LT}	SHEAR MODULUS (MSI)TANGENT G_{TAN}	SHEAR MODULUS (MSI)SECANT G_{SEC}
0.	0.	0.0	0.0
1265.	1602.	0.789834	0.789834
2511.	3220.	0.770100	0.779918
3747.	4860.	0.753753	0.771088
4950.	6520.	0.724548	0.759239
6087.	8200.	0.676494	0.742286
7119.	9900.	0.607384	0.719121
8011.	11620.	0.518687	0.689452
8707.	13320.	0.409312	0.653699
9255.	15057.	0.315170	0.614645
9703.	16820.	0.254113	0.576856
10447.	20400.	0.207833	0.512096
11120.	24290.	0.172960	0.457784
11722.	28480.	0.143794	0.411589

Longitudinal Flexure and Interlaminar Shear Data

Treated Graphite Fiber Laminates (Type AS/3002)

Table XV presents longitudinal flexure and interlaminar shear strength data for unidirectional Type AS/3002 batch treated graphite/epoxy laminates. Four test temperatures were used, namely, -65°F, room temperature, 265°F, and 350°F. Also, four different lots of material were tested, and the average test values were recorded for each temperature and lot used. All test values exceeded specification requirements as given in Specification ST0130LB0005 and presented in table XV. Figure 56 shows a plot of both longitudinal flexure and interlaminar shear strengths as a percentage of room temperature values versus test temperature. The interlaminar shear strength, as expected, decreases with increasing temperature, while the longitudinal flexure strength remains fairly constant up to a temperature of 265°F, and then begins to fall off.

Untreated Graphite Fiber Laminates (Type A/3002)

Table XVI presents longitudinal flexure and interlaminar shear strength data for unidirectional Type A/3002 batch untreated graphite/epoxy laminates tested at various temperatures (-65°F, room temperature, 265°F, and 350°F). Only one lot of material was tested, and the test values were compared to the specification requirement (ST0130LB0005). (Refer to appendix I.) In general, the flexure strengths were well above the specification requirements, while the interlaminar shear strengths were up to 24 percent lower than required. Figure 57 shows a plot of interlaminar shear and flexure strengths (as a percentage of room temperature values) versus temperature. The general trend is one of decreasing strength with increasing temperature, with both interlaminar shear and flexure strengths being reduced by 20 percent at 350°F.

TABLE XV. LONGITUDINAL FLEXURE AND INTERLAMINAR SHEAR DATA (TYPE AS/3002 BATCH) UNIDIRECTIONAL $[0]_{13T}$

Parameters	Lot No.				Avg	Specification ST0130LB0005 Requirement
	1B-57A	1B-57B	1B-57C	1C-94		
Date Received	6-11-71	6-30-71	7-1-71	10-6-71		
Quantity (lb)	4.23	21.0	36.5	11.3		
Longitudinal Flexure (Ksi)						
RT	227.9 (3)*	219.3 (3)	220.0 (3)	221.9 (3)	222.3 (12)	200.0
265° F	222.2 (3)				222.2 (3)	
350° F	193.0 (3)	181.9 (3)		219.8 (3)	198.2 (9)	150.0
-65° F						
Horizontal Shear (Ksi)						
RT	18.5 (3)*	18.1 (3)	17.8 (3)	17.4 (3)	18.0 (12)	13.0
265° F	11.6 (3)				11.6 (3)	
350° F	9.8 (3)	9.3 (3)	11.6 (3)	8.7 (3)	9.9 (12)	8.0
-65° F			20.2 (5)		20.2 (5)	

*Average of ( ) specimens

TABLE XVI. UNIDIRECTIONAL GRAPHITE/EPOXY LONGITUDINAL FLEXURE AND INTERLAMINAR SHEAR DATA

(TYPE A/3002 BATCH - UNTREATED FIBER) LOT NO. 1A-65 - $[0]_{13T}$

Test Orientation	Temperature (°F)			
	-65	RT	265	350
Longitudinal		257.5	220.9	199.5
Flexure (Ksi)		255.6	250.7	202.1
		245.4	225.6	184.9
Average		(252.8)	(223.3)	(195.5)
Specification Requirement		200.0		150.0
Horizontal	8.2	11.1	7.9	7.7
Shear (Ksi)	9.7	9.6	9.2	7.8
(short beam)	8.9	8.9	7.7	8.3
Average	(8.9)	(9.9)	(8.3)	(7.9)
Specification Requirement		13.0		8.0

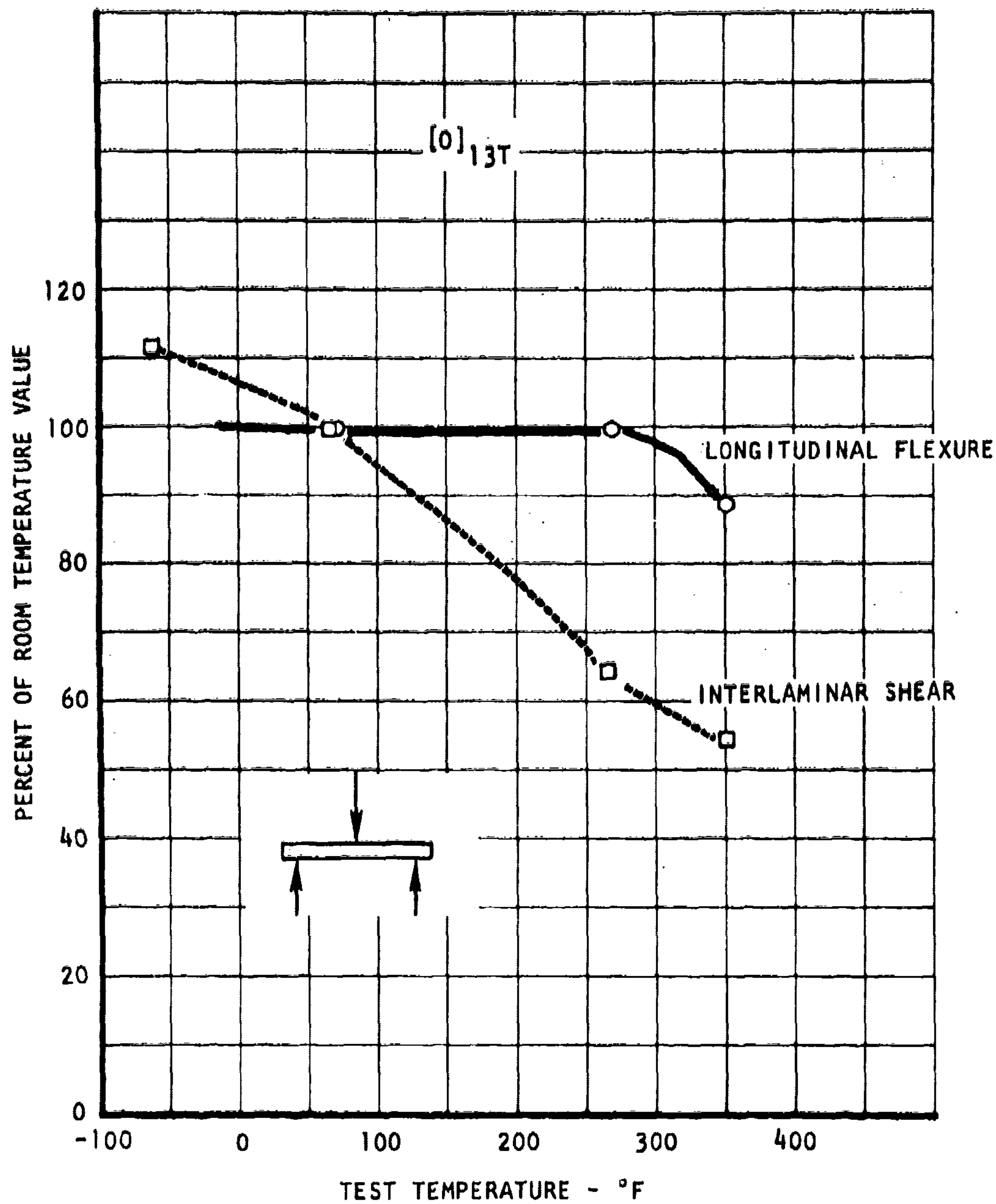


Figure 56. Graphite/Epoxy - Effect of Test Temperature on Longitudinal Flexure and Interlaminar Shear Properties - Type AS/3002 - Batch

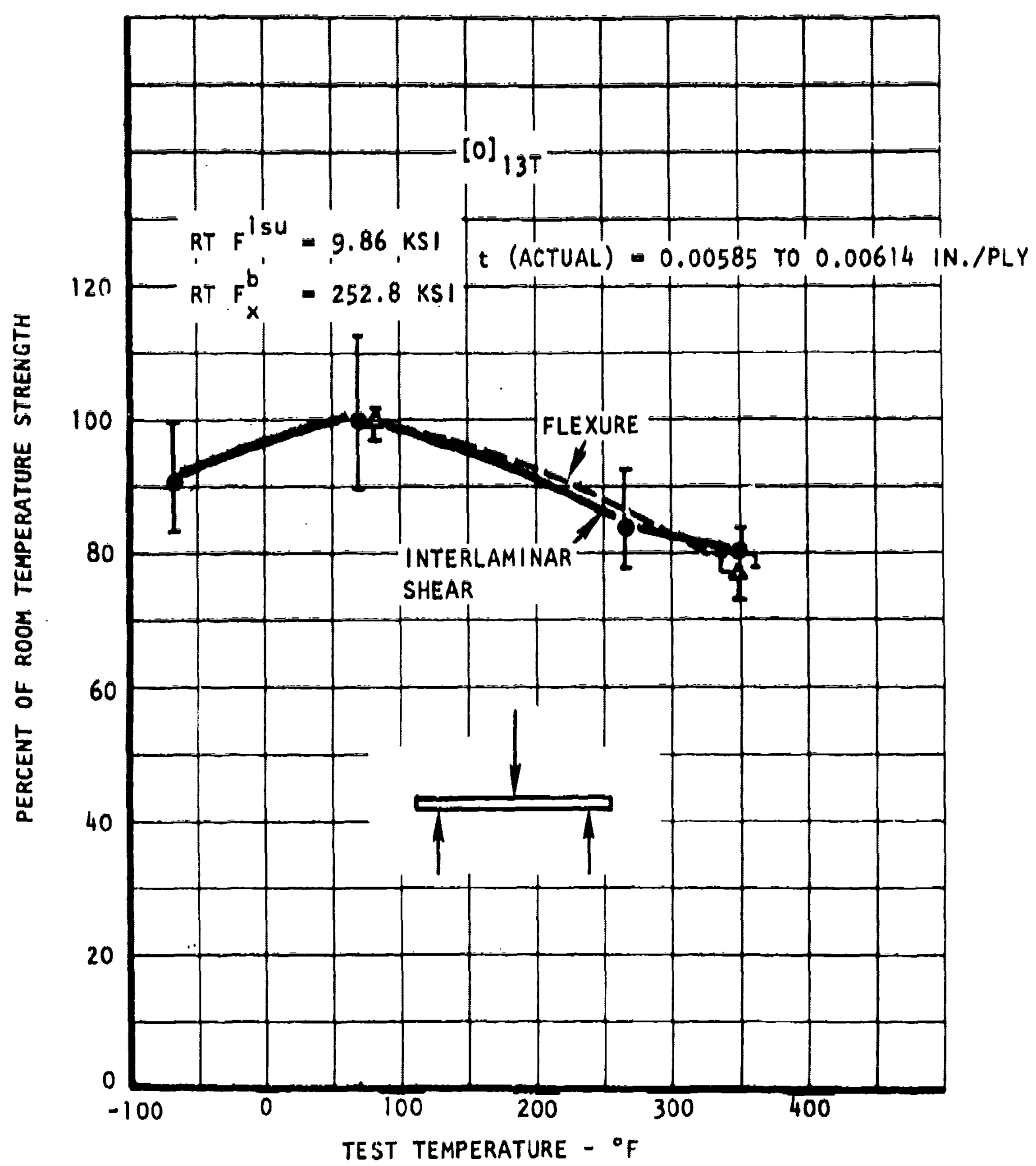


Figure 57. Graphite/Epoxy - Effect of Test Temperature on Flexure and Interlaminar Shear Properties - Type A/3002 Batch - Untreated Fiber

CROSSPLY PROPERTIES

Tension Properties

Treated Graphite Fiber Laminates (Type AS/3002)

Tension coupon data for various crossplied Type AS/3002 batch graphite/epoxy laminate orientations are presented in tables XVII, XVIII, and XIX. Tests were run for $[0/\pm45]_S$, $[90/\pm45]_S$, $[0/\pm45/90]_S$, $[\pm45]_{2S}$, and $[0_2/\pm45/90]_S$ laminate orientations, with -65°F, room temperature, and 350°F tension tests being run for each orientation. In general, the modulus values were all greater than or equal to the predicted values (section V). The room temperature and 350°F average tensile strengths were also in good agreement with predicted values (within 20 percent). On the other hand, the -65°F tensile strengths were much lower than expected (36 to 47 percent lower) with the only exceptions being the transverse $[0/\pm45]_S$ and $[\pm45]_{2S}$ laminate tensile strengths which were in agreement with the predicted values. These low -65°F tension strengths could be due in part to data scatter as only one -65°F specimen was tested per orientation. Typical -65°F, room temperature, and 350°F tension coupons are shown in figures 58, 59, and 60, respectively. Furthermore, typical stress-strain curves for the three test temperatures are presented in figures 61, 62, 63, and 64.

Table XX contains tension sandwich bending beam data for $[0/\pm45]_S$, $[90/\pm45]_S$, $[\pm45]_{2S}$, $[0/\pm45/90]_S$, and $[0_2/\pm45/90]_S$ graphite/epoxy laminate orientations. In general, the strength values obtained were 20 to 189 percent higher than predicted, probably due to the fact that the predicted value is based primarily on tension coupon data. Typical failed beam specimens are shown in figures 65 and 66. Comparisons of sandwich beam tension data (table XIX) with the IITRI tension coupon data show that, in all cases, the beam data (table XX) exhibited higher average strength levels (114 to 207 percent of tension coupon data). This indicates that the localized stress concentrations inherent in tension coupon tests serve to reduce apparent ultimate strengths.

Untreated Graphite Fiber Laminates (Type A/3002)

Crossplied tension coupon data for longitudinal and transverse $[0/\pm45/90]_S$, Type A/3002 (untreated) batch graphite/epoxy laminates are presented in table XXI. Three test temperatures were used; namely, -65°F, room temperature, and 350°F. In general, the modulus values were in fairly good agreement with predicted modulus values (within 10 percent). The strength values, however, were 9 to 39 percent lower than predictions based on treated fiber data.

TABLE XVII. CROSSPLIED GRAPHITE/EPOXY IITRI TENSION COUPON DATA (TYPE AS/3002 BATCH $[0/\pm45]_S$ AND $[90/\pm45]_S$)

Test Orientation	Specimen No.	Thickness (In.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus E (Msi)	Ultimate Strain - (μ in./in.)	Test/Predicted*** Strength	Modulus
$[0/\pm45]_S$	T-6L-1	0.0360	RT	60.3	8.22*	8,250	0.861	1.111
6 plies	T-6L-2	0.0364	RT	71.1	8.62*	9,150	1.016	1.165
	T-6L-3	0.0370	RT	67.1	7.20**	9,500	0.959	0.973
	Avg			(66.2)	(8.01)	(8,967)	(0.946)	(1.083)
	T-6L-4	0.0366	350	52.0	6.49*	8,610	0.912	1.030
	T-6L-5	0.0370	350	65.4	7.47*	8,490	1.147	1.186
	Avg			(58.7)	(6.98)	(8,550)	(1.030)	(1.108)
	T-6L-6	0.0375	-65	(37.0)	(8.75)**	(4,400)	(0.528)	(1.182)
$[90/\pm45]_S$	T-6T-1	0.0356	RT	32.1	4.10*	8,880	1.235	1.171
6 plies	T-6T-2	0.0336	RT	31.7	3.75**	10,300	1.219	1.071
	T-6T-3	0.0356	RT	31.9	3.56*	10,500	1.227	1.017
	Avg			(31.9)	(3.80)	(9,893)	(1.227)	(1.086)
	T-6T-4	0.0360	350	22.8	3.03*	9,450	1.140	1.165
	T-6T-5	0.0315	350	20.9	2.33*	8,850	1.045	0.896
	Avg			(21.9)	(2.68)	(9,150)	(1.095)	(1.031)
	T-6T-6	0.0317	-65	(25.5)	(3.90)**	(6,600)	(0.981)	(1.114)

* Extensometer data
** Strain gage data
*** Predicted value (Refer to section V.)

TABLE XVIII. CROSSPLIED GRAPHITE/EPOXY IITRI TENSION COUPON DATA (TYPE AS/3002 BATCH $[0/\pm45/90]_S$ AND $[90/\pm45/0]_S$)

Test Orientation	Specimen No.	Thickness (In.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus E (Msi)	Ultimate Strain - (μ in./in.)	Test/Predicted*** Strength	Test/Predicted*** Modulus
$[0/\pm45/90]_S$ Tension Coupon	T-8L-1	0.0485	RT	58.8	7.50*	8,800	0.918	1.119
	T-8L-2	0.0475	RT	47.6	7.54*	7,240	0.744	1.125
	T-8L-3	0.0470	RT	56.1	7.60**	7,700	0.877	1.134
	Avg			(54.2)	(7.54)	(7,910)	(0.847)	(1.125)
8 Plies Load - TL	T-8L-4	0.0478	350	54.5	7.52*	8,800	1.009	1.397
	T-8L-5	0.0480	350	58.7	6.50**	9,300	1.087	1.121
	Avg			(56.6)	(7.01)	(9,050)	(1.048)	(1.209)
	T-8L-6	0.0480	-65	(39.6)	--	--	(0.619)	--
$[90/\pm45/0]_S$ Tension coupon	T-8T-1	0.0475	RT	51.4	7.26*	7,340	0.823	1.084
	T-8T-2	0.0475	RT	48.1	7.92*	6,880	0.752	1.182
	T-8T-3	0.0475	RT	50.9	6.50**	7,900	0.795	0.970
	Avg			(50.1)	(7.23)	(7,373)	(0.783)	(1.079)
8 Plies Load - TT	T-8T-4	0.0480	350	61.3	6.73*	9,690	1.135	1.160
	T-8T-5	0.0475	350	65.8	6.75**	10,000	1.219	1.164
	Avg			(63.6)	(6.74)	(9,845)	(1.178)	(1.162)
	T-8T-6	0.0480	-65	(42.5)	(7.5)**	(5,700)	(0.664)	(1.119)
$[0/\pm45/90]$	Avg (6)		RT	(52.2)	(7.39)	(7,640)	(0.816)	(1.102)
	Avg (4)		350	(60.1)	(6.88)	(9,450)	(1.113)	(1.185)
	Avg (2)		-65	(41.1)	(7.5)	(5,700)	(0.642)	(1.119)

NOTE TL = longitudinal tension; TT = transverse tension
* Extensometer data
** Strain gage data
*** Predicted value (refer to section V.)

TABLE XIX. CROSSPLIED GRAPHITE/EPOXY IITRI TENSION COUPON DATA (TYPE AS/3002 BATCH $[\pm45]_{2S}$ AND $[0_2/\pm45/90]_S$)

Test Orientation	Specimen No.	Thickness (In.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus E (Msi)	Ultimate Strain - (μ in./in.)	Test/Predicted***	
							Strength	Modulus
$[\pm45]_{2S}$ Tension Coupon 8 Plies	T-8AL-1	0.0460	RT	26.2	2.81*	23,220	1.139	1.171
	T-8AL-2	0.0435	RT	25.7	2.98*	19,800	1.117	1.242
	T-8AL-3	0.0444	RT	27.0	2.80**	18,000	1.174	1.167
	Avg			(26.3)	(2.86)	(20,340)	(1.143)	(1.192)
Load - TL	T-8AL-4	0.0460	350	17.4	1.21*	58,200	1.450	1.008
	T-8AL-5	0.0470	350	16.1	1.22*	53,580	1.342	1.017
	Avg			(16.7)	(1.21)	(55,890)	(1.392)	(1.008)
	T-8AL-6	0.0450	-65	24.5	2.70**	9,800	(1.065)	(1.125)
$[0_2/\pm45/90]_S$ Tension coupon	T-10L-1	0.0580	RT	80.1	10.05*	8,250	0.965	1.155
	T-10L-2	0.0600	RT	85.0	9.54*	1,020	1.024	1.097
	T-10L-3	0.0602	RT	71.8	9.00*	8,300	0.865	1.034
	Avg			(79.8)	(9.53)	(8,917)	(0.951)	(1.095)
10 plies Load - TL	T-10L-4	0.0605	350	84.6	9.71*	9,120	1.175	1.229
	T-10L-5	0.0606	350	76.6	9.15*	8,850	1.064	1.158
	Avg			(80.6)	(9.43)	(8,985)	(1.119)	(1.194)
	T-10L-6	0.0600	-65	(45.8)	(9.87)	(5,050)	(0.552)	(1.134)

NOTE TL = longitudinal tension; TT = transverse tension
* Extensometer data
** Strain gage data
*** Predicted value (Refer to section V.)

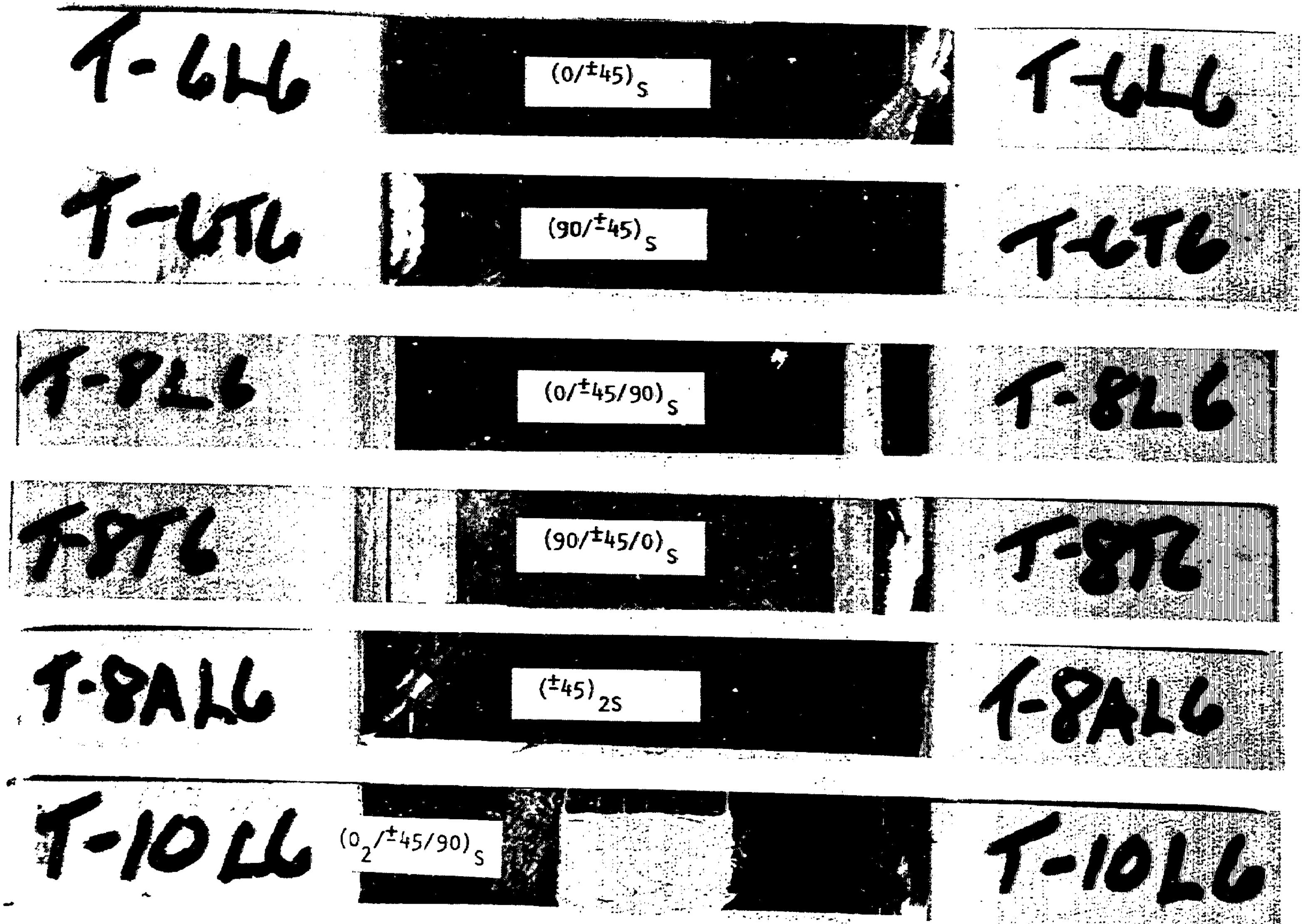


Figure 58. Typical Failed Tension Coupons - Crosspiled Graphite/Epoxy - Type AS/3002 - Batch - Various Orientations, -65°F

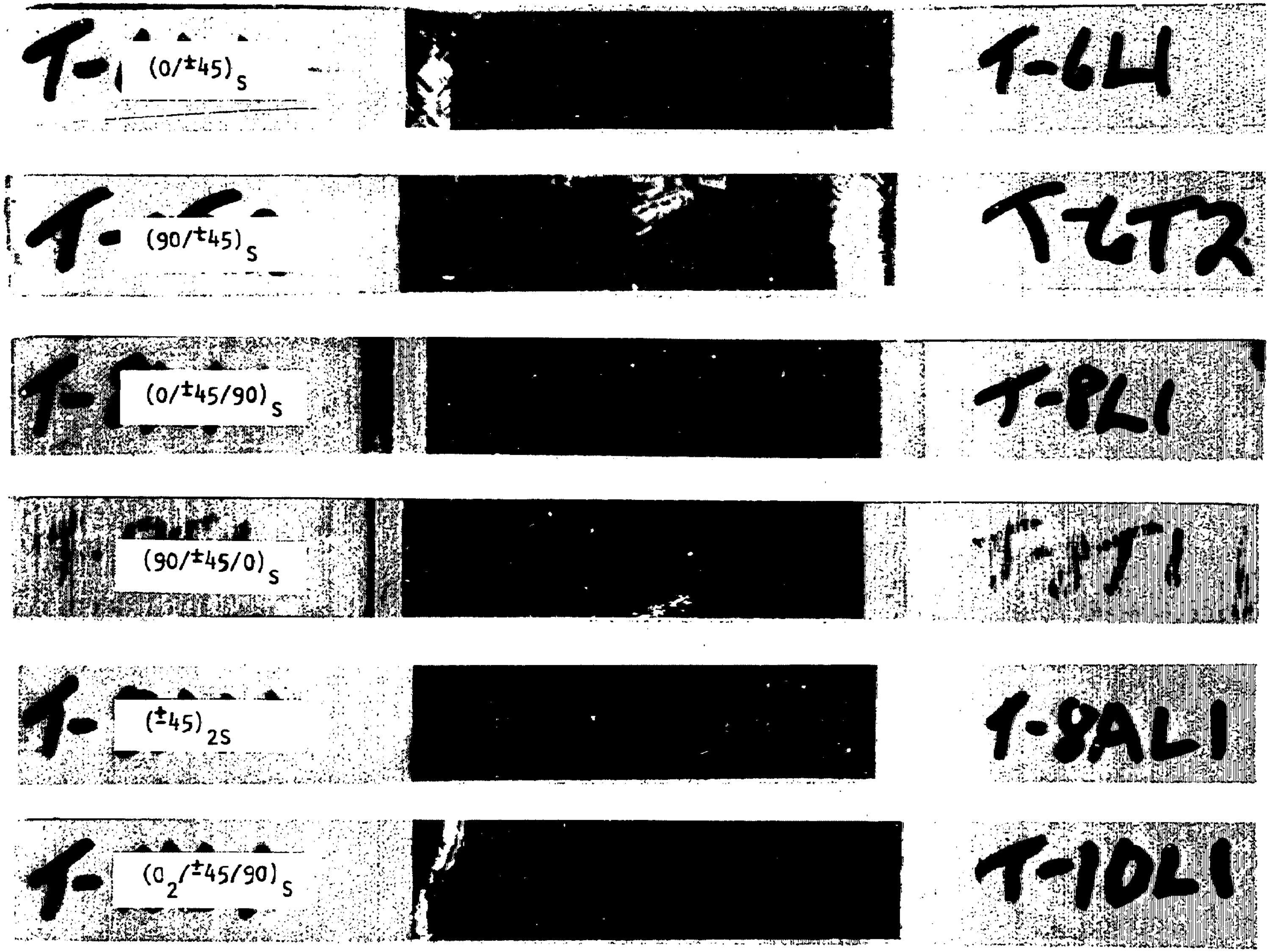


Figure 59. Typical Failed Tension Coupons - Crossplied Graphite/Epoxy - Type AS/3002 - Batch - Various Orientations, Room Temperature

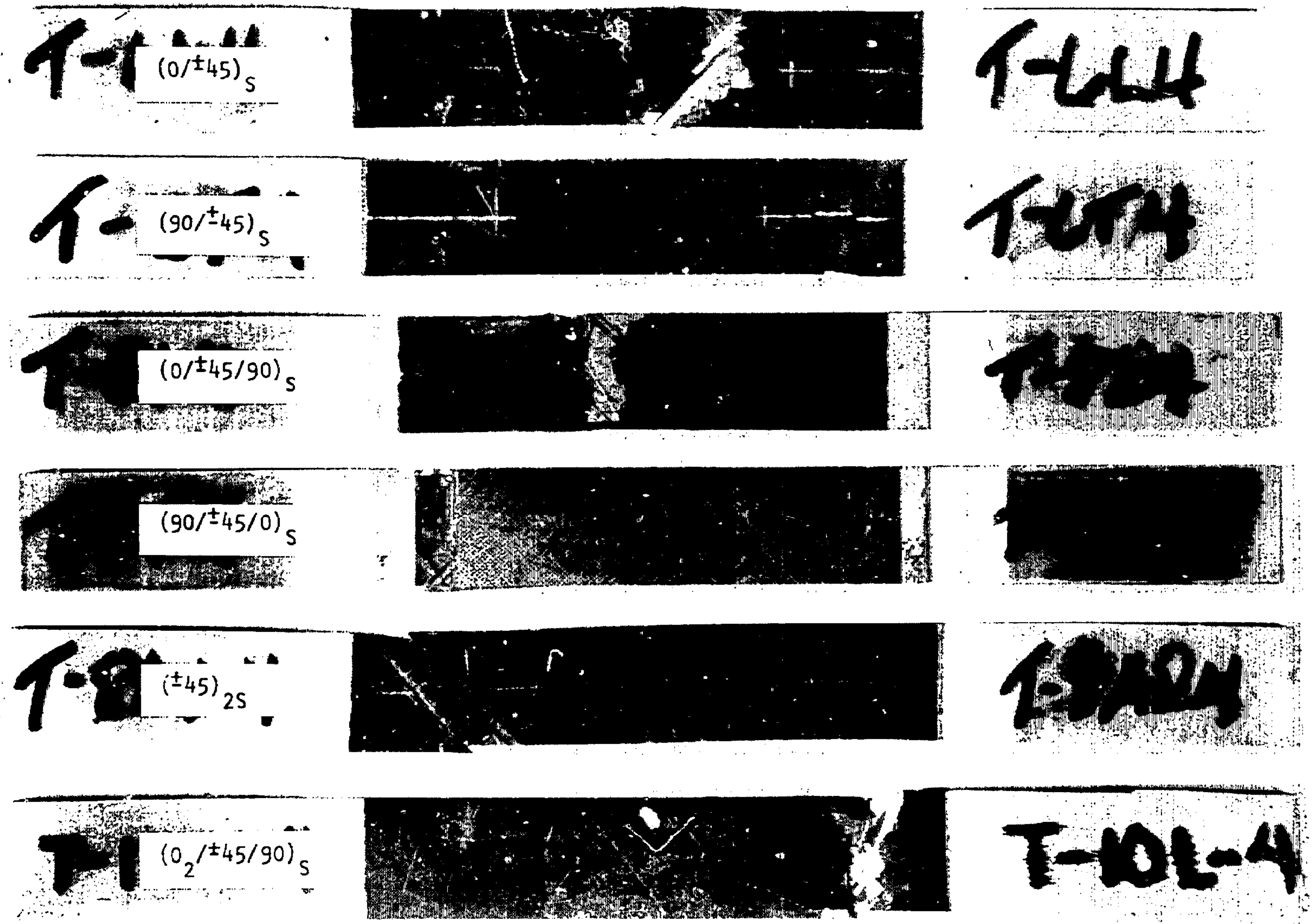


Figure 60. Typical Failed Tension Coupons - Crossplied Graphite/Epoxy - Type AS/3002 - Batch --Various Orientations, 350°F

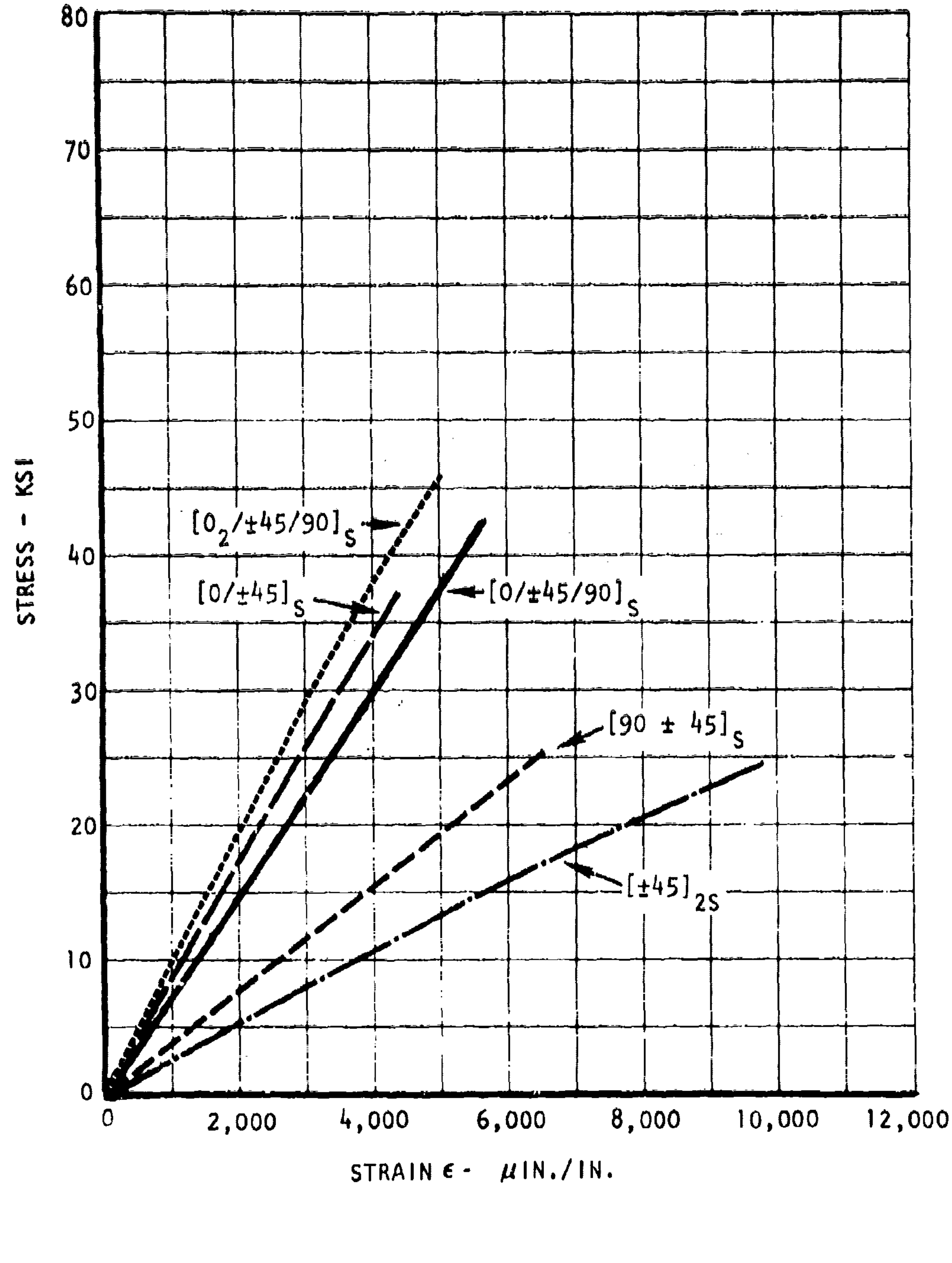


Figure 61. Crossplied Graphite/Epoxy Typical Tension Stress-Strain Curves - Various Laminate Orientations - -65°F (Type AS/3002 - Batch)

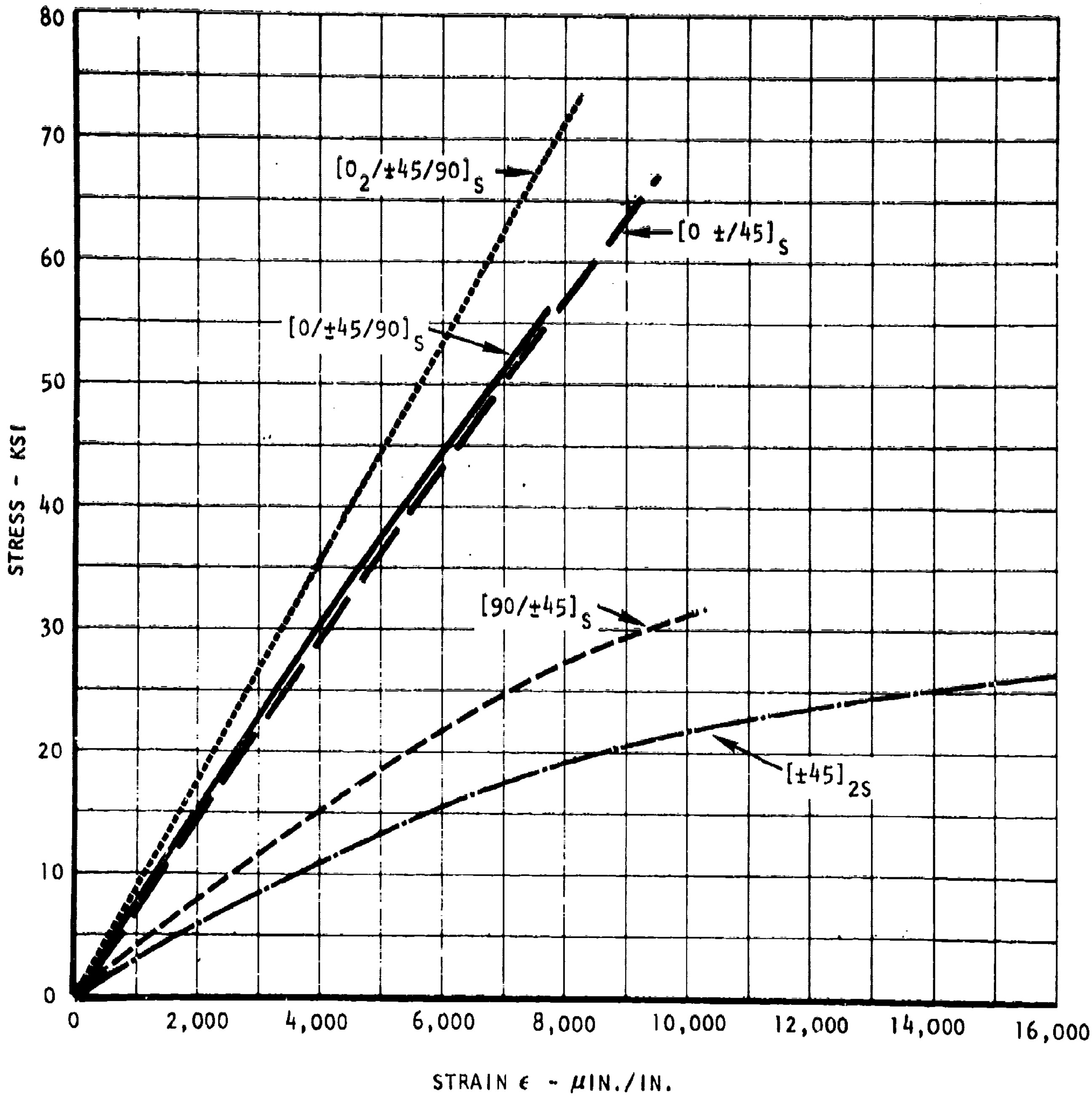


Figure 62. Crossplied Graphite/Epoxy Typical Tension Stress-Strain Curves - Various Laminate Orientations - Room Temperature (Type AS/3002 - Batch)

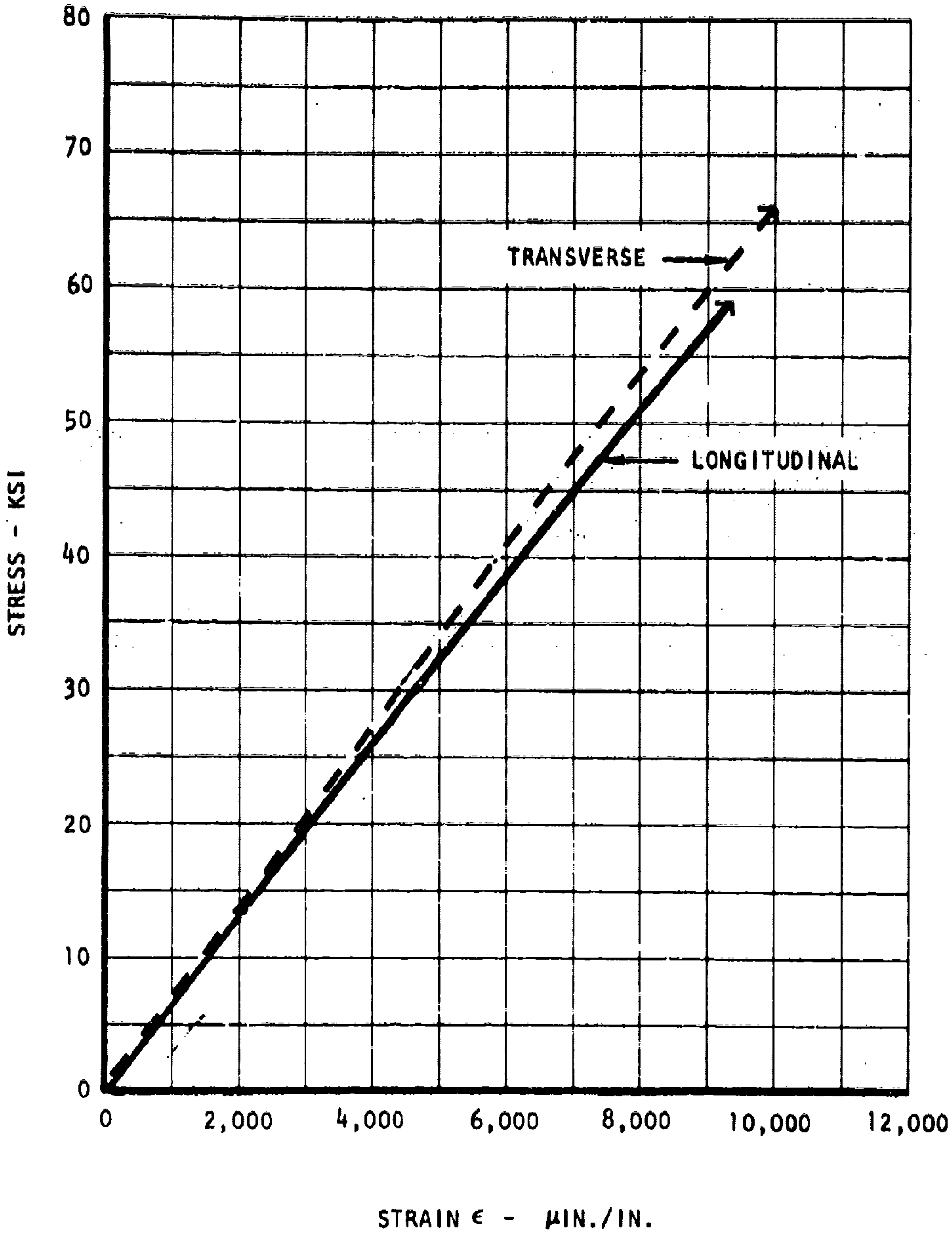


Figure 63. Crossplied Graphite/Epoxy Typical Tension Stress-Strain Curves - $[0/\pm45/90]_S$ Laminate Orientation - 350°F (Type AS/3002 - Batch)

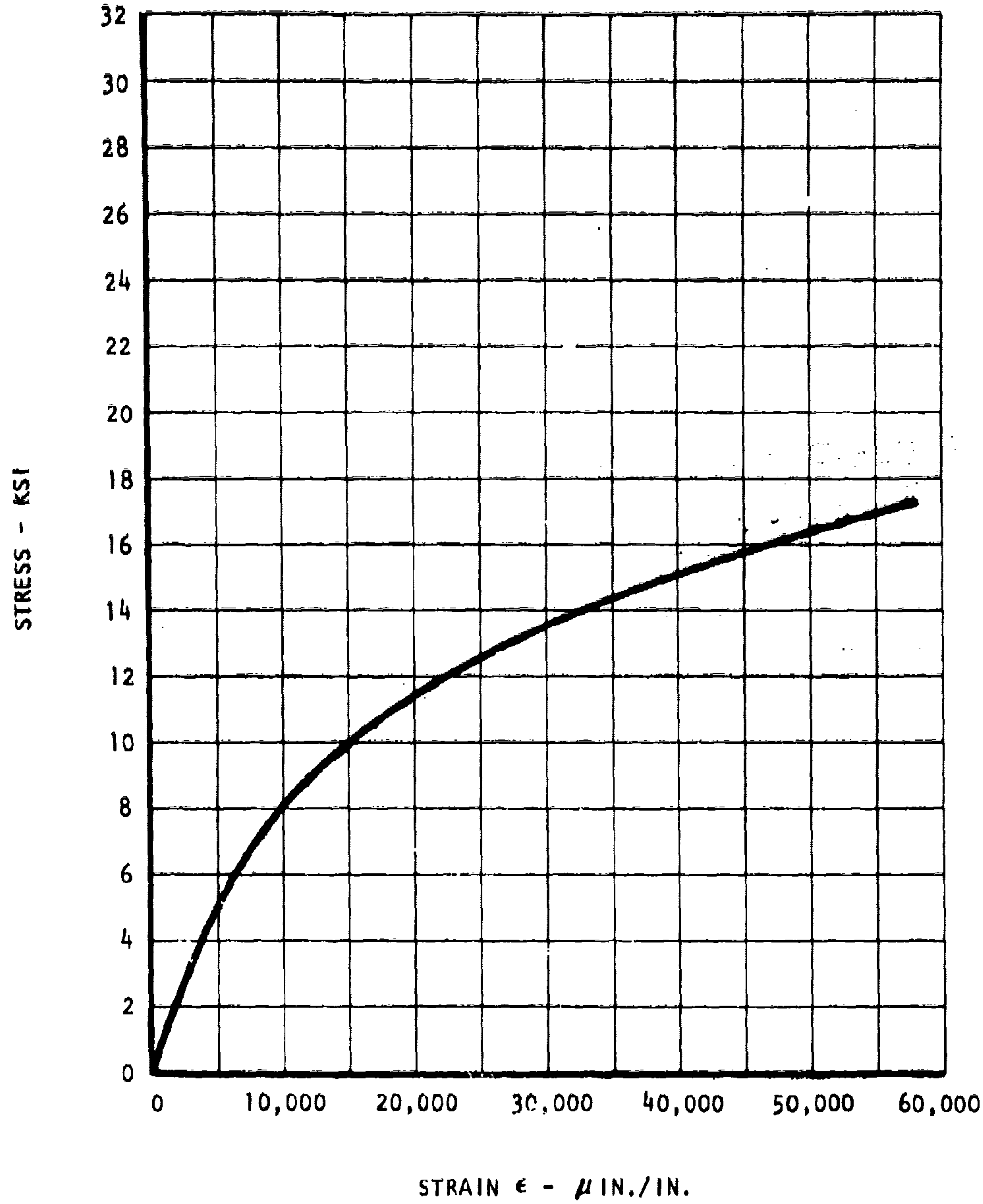


Figure 64. Crossplied Graphite/Epoxy Typical Tension Stress-Strain Curves - $[\pm 45]_{2S}$ Laminate Orientation - 350° F (Type AS/3002 - Batch)

TABLE XX. GRAPHITE/EPOXY SANDWICH BENDING BEAM SPECIMEN TENSION DATA (TYPE AS/3002 BATCH)

Test Orientation	Specimen No.	Thickness* (In.)	Width W (In.)	Temp (°F)	Max Load (lb)	Stress (Ksi)	Test/Predicted*** Strength	Test/Predicted*** Failure Mode**
$[0/\pm45]_S$	TLBB-6L1	0.036	0.997	RT	1,375	98.36	1.405	T
	TLBB-6L2	0.036	0.996	350	1,150	82.34	1.444	T
$[90/\pm45]_S$	TLBB-6T1	0.036	0.984	RT	855	61.97	2.383	TO
	TLBB-6T2	0.036	1.000	350	400	28.53	1.426	T, S
$[\pm45]_{2S}$	TLBB-8AL1	0.048	1.000	RT	765	40.76	1.772	T
	TLBB-8AL2	0.048	1.000	350	650	34.63	2.886	T
$[0/\pm45/90]_S$	TLBB-8L1	0.048	0.997	RT	1,530	81.77	1.277	T
	TLBB-8L2	0.048	1.007	350	1,220	64.55	1.195	B
$[0_2/\pm45/90]_S$	TLBB-10L1	0.060	0.994	RT	2,400	102.52	1.235	T
	TLBB-10L2	0.060	1.007	350	1,310	55.24	0.767	B

NOTE

*Nominal face sheet thickness
**T = tension failure in test section
*** = Predicted value (Refer to section V.)
B = core-to-face sheet bond failure
TO = tension failure outside test section
S = face sheet interlaminar shear failure

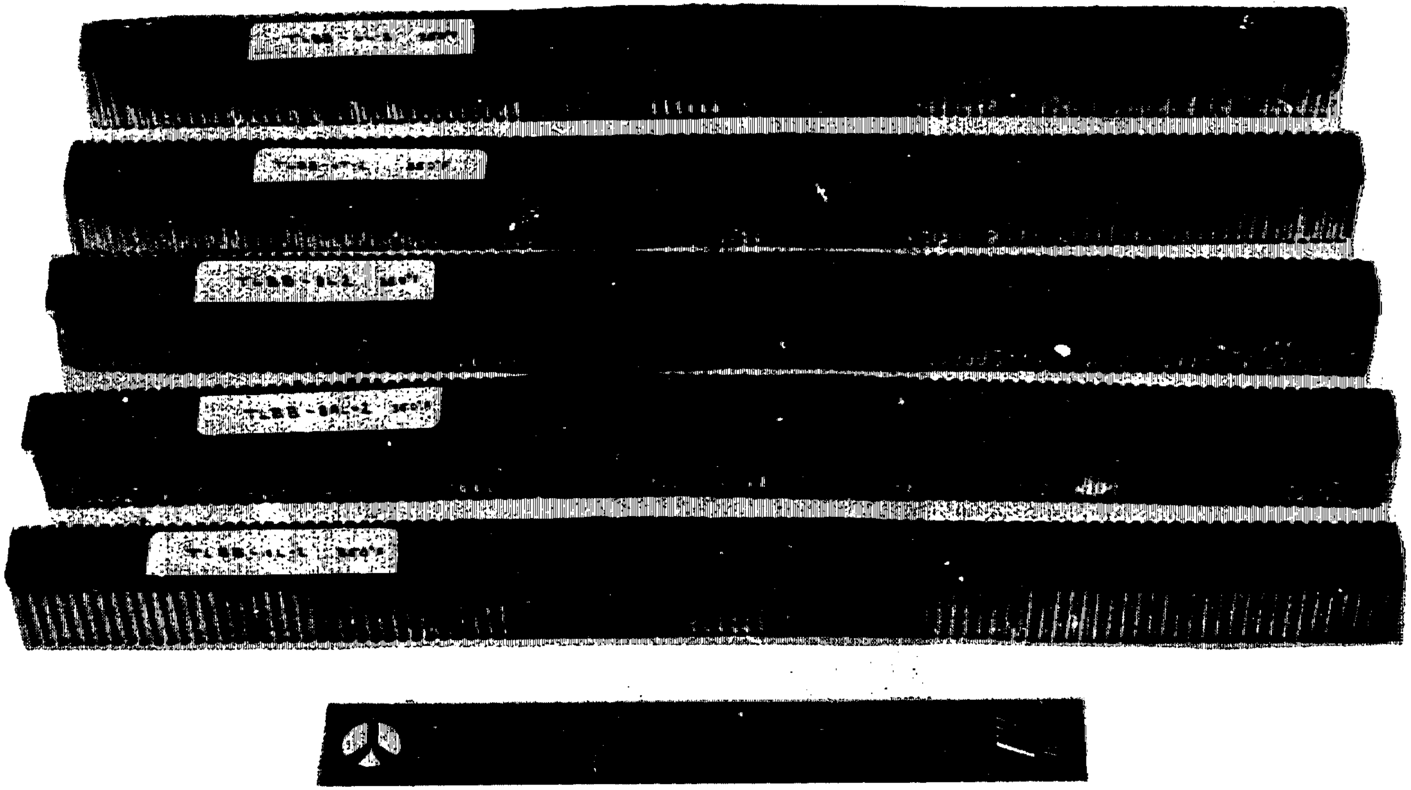


Figure 65. Crossplied Graphite/Epoxy Tension Bending Beam Specimens - Room Temperature - (Type AS/3002 - Batch)

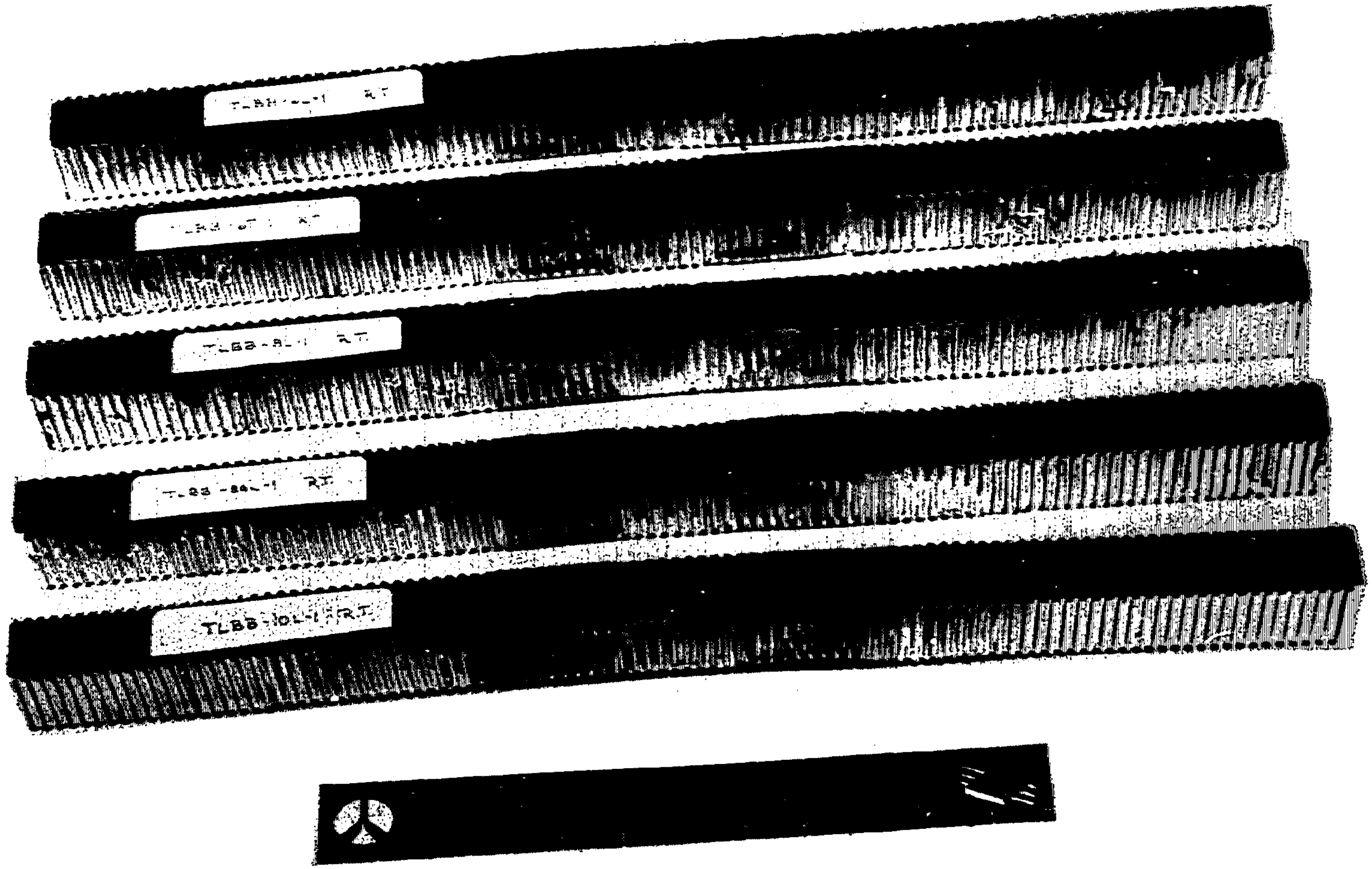


Figure 66. Crossplied Graphite/Epoxy Tension Bending Beam Specimens - 350°F - (Type AS/3002 - Batch)

TABLE XXI. CROSSPLIED GRAPHITE/EPOXY IITRI TENSION COUPON DATA (TYPE A/3002 BATCH - UNTREATED FIBER)

Test Orientation	Specimen No.	Thickness (In.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus E (Msi)	Ultimate Strain - (μ in./in.)	Test/Predicted*** Strength	Test/Predicted*** Modulus
$[0/\pm45/90]_S$	T-8L-1	0.049	RT	55.9	7.79*	8,020	0.873	1.163
Tension	T-8L-2	0.049	RT	56.7	6.98**	8,408	0.886	1.042
coupon	T-8L-5	0.049	RT	52.3	6.74*	8,060	0.817	1.006
8 plies	Avg			(55.0)	(7.17)	(8,163)	(0.859)	(1.070)
Load - TL	T-8L-3	0.049	350	48.1	6.55*	8,040	0.891	1.129
	T-8L-4	0.049	350	50.5	6.30**	8,340	0.935	1.086
	Avg			(49.3)	(6.43)	(8,190)	(0.913)	(1.109)
	T-8L-6	0.049	-65	(46.6)	(6.00)*	(7,770)	(0.728)	(.896)
$[90/\pm45/0]_S$	T-8T-1	0.049	RT	36.4	7.72*	5,860	0.569	1.152
Tension	T-8T-2	0.049	RT	42.2	6.60**	6,360	0.659	0.985
coupon	T-8T-5	0.049	RT	48.3	6.25*	7,720	0.755	0.933
8 plies	Avg			(42.3)	(6.86)	(6,647)	(0.661)	(1.024)
Load - TT	T-8T-3	0.049	350	42.3	6.27*	6,675	0.783	1.081
	T-8T-4	0.048	350	48.6	6.52**	7,530	0.900	1.124
	Avg			(45.5)	(6.40)	(7,102)	(0.843)	(1.103)
	T-8T-6	0.049	-65	(39.2)	(6.43)	(6,200)	(0.613)	(.960)

NOTE TL = longitudinal tension; TT = transverse tension
* Extensometer data
** Strain gage data
*** Predicted value (Refer to section V.)

Compression Properties

Treated Graphite Fiber Laminates (Type AS/3002)

Edgewise sandwich compression specimen data for -65°F, room temperature, and 350°F tests of $[90/\pm45]_S$, Type AS/3002 batch graphite/epoxy laminates are presented in table XXII. All failures were a combination of face sheet buckling and laminate delaminations. All 350°F and -65°F modulus and strength values were greater than predicted and the room temperature strengths were on the average slightly lower than predicted. Photographs of the failed specimens are included as figures 67, 68, and 69.

Compression sandwich bending beam specimens were also tested and the test data are presented in table XXIII. The $[0/\pm45]_S$ and $[0/\pm45/90]_S$ laminates were tested at -65°F, room temperature, and 350°F. The strength values obtained were, on the average, 45 to 95 percent higher than predicted, while the modulus values were close to the predicted values (within 20 percent). Typical failed specimens are shown in figures 70 and 71, and typical room temperature and 350°F stress-strain curves for the two orientations are presented in figures 72 and 73.

Untreated Graphite Fiber Laminates (Type A/3002)

The $[0/\pm45/90]_S$ graphite/epoxy Type A/3002 laminate edgewise compression sandwich specimen test data for room temperature and 350°F are presented in table XXIV. The average room temperature strength was found to be 18 percent less than predicted, while the 350°F average strength was 53 percent greater than predicted. Note that the strengths were considerably lower than those obtained for the same laminate orientation fabricated from treated (Type AS/3002) graphite/epoxy, (table XXIII), based on sandwich beam tests. The test method, edgewise compression versus sandwich beam, rather than type of fiber appears to be the reason for the higher strengths obtained with sandwich beams.

TABLE XXII. GRAPHITE/EPOXY EDGEWISE SANDWICH COMPRESSION SPECIMEN COMPRESSION DATA (TYPE AS/3002 BATCH) - $[90/\pm45]_S$

Specimen No.	Thickness* (In.)	Width W (In.)	Height H (In.)	Temp (°F)	F^{cu} (Ksi)	Modulus** (Msi)	Ultimate Strain** (μin./in.)	Test/Predicted***	
								Stress	Modulus
EC-6T-1	0.036	2.435	3.650	RT	36.90	6.15	6,164	0.92	1.81
EC-6T-2	0.036	2.675	3.650	RT	33.59	6.49	6,493	0.84	1.91
EC-6T-3	0.036	2.685	3.652	RT	40.40	5.86	7,106	1.01	1.72
Ave					(36.96)	(6.17)	(6,588)	(0.92)	(1.82)
EC-6T-4	0.036	2.435	3.650	350	33.60	4.35	8,219	1.53	1.67
EC-6T-5	0.036	2.685	3.650	350	33.52	4.08	8,219	1.52	1.57
Ave					(33.56)	(4.22)	(8,219)	(1.52)	(1.62)
EC-6T-6	0.036	2.460	3.650	-65	(44.99)	(5.76)	(9,041)	---	---

NOTE:

*Nominal face sheet, based on a nominal ply thickness of 0.006 inch

**Calculated from head deflection extensometer data

***Predicted values (Refer to section V.)

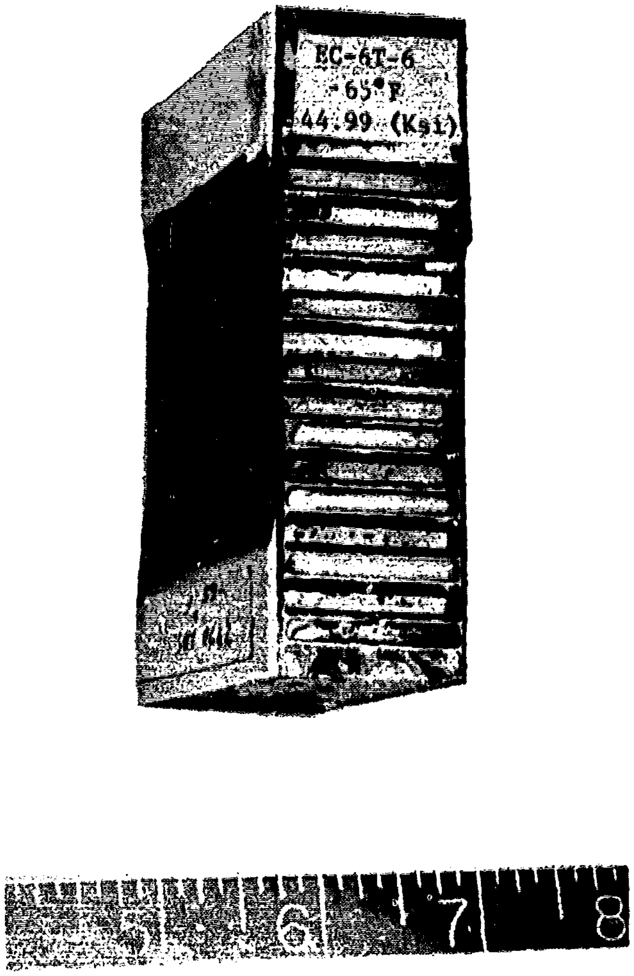


Figure 67. Failed $[90/\pm45]_S$ -65°F Edgewise Compression Specimens - Type AS/3002 - Batch, Graphite/Epoxy

Figure 68. Failed $[90/\pm45]_S$ Room Temperature Edgewise Compression Specimens - Type AS/3002 - Batch, Graphite/Epoxy

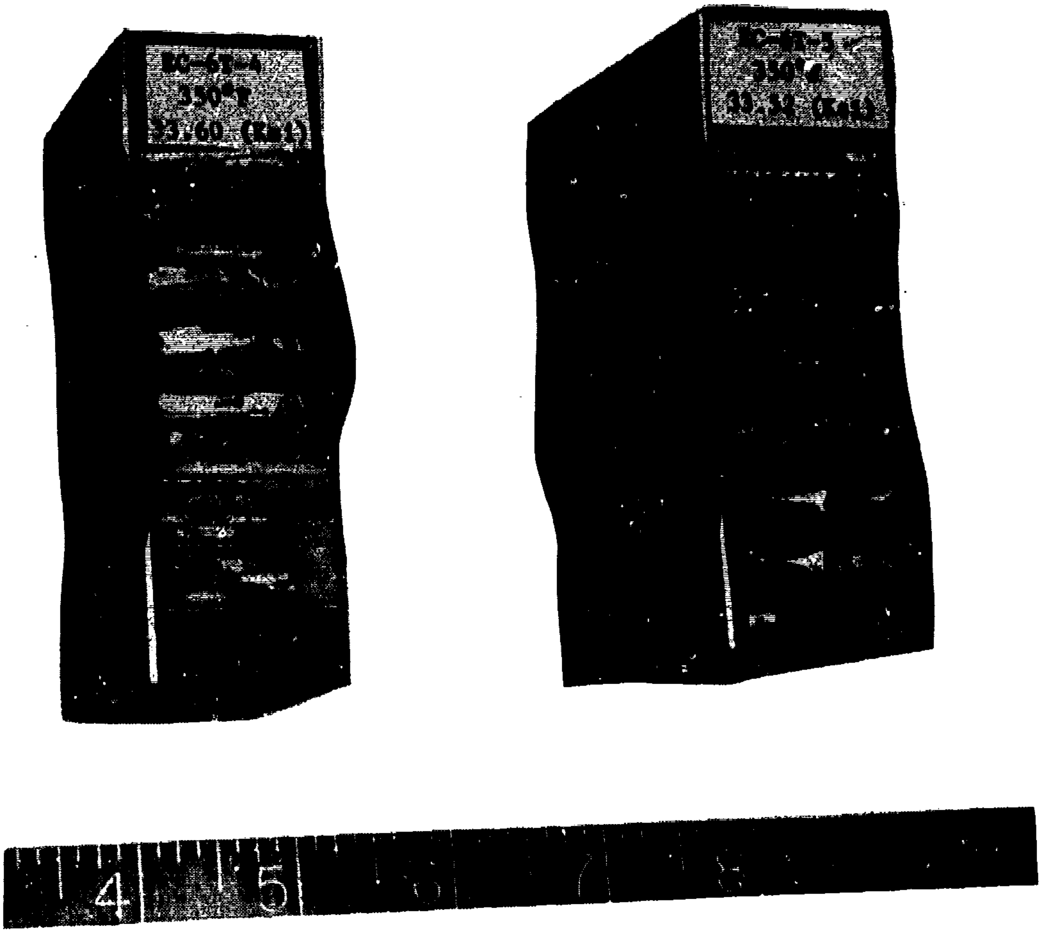


Figure 69. Failed $[90/\pm45]_S$ 350°F Edgewise Compression Specimens - Type AS/3002 - Batch, Graphite/Epoxy

TABLE XXIII. GRAPHITE/EPOXY CROSSPLIED COMPRESSION BENDING BEAM DATA (TYPE AS/3002 BATCH)

Test Orientation	Specimen No.	Thickness* (In.)	Width (In.)	Temp (°F)	Stress (In.)	Modulus** (Msi)	Ultimate Strain** (μin./in.)	Test/Predicted*** Stress	Test/Predicted*** Modulus	Failure Mode - Face Sheet Compression Failure
$[0/\pm45]_S$	CLBB-6L-1	0.036	0.995	RT	111.81	---	---	1.53	---	In test area
	CLBB-6L-2	0.036	0.990	RT	109.14	---	---	1.50	---	In test area
	CLBB-6L-3	0.036	0.990	RT	129.67	8.9	16,500	1.77	1.20	In test area
	Avg				(116.87)	(8.9)	(16,500)	(1.60)	(1.20)	
	CLBB-6L-4	0.036	0.990	350	78.16	---	---	2.23	---	Outside test area
	CLBB-6L-5	0.036	0.995	350	43.72	5.7	9,000	1.25	0.91	In test area
	Avg				(60.94)	(5.7)	(9,000)	(1.74)	(0.91)	
	CLBB-6L-6	0.036	0.995	-65	130.45	---	---	1.79	---	In test area
$[0/\pm45/90]_S$	CLBB-8L-1	0.048	0.905	RT	92.14	---	---	1.40	---	In test area
	CLBB-8L-2	0.048	0.900	RT	104.49	---	---	1.58	---	In test area
	CLBB-8L-3	0.048	0.905	RT	91.26	7.0	16,000	1.38	1.06	In test area
	Avg				(95.96)	(7.0)	(16,000)	(1.45)	(1.06)	In test area
	CLBB-8L-4	0.048	0.905	350	55.93	---	---	1.80	---	In test area
	CLBB-8L-5	0.048	0.985	350	64.90	5.8	12,200	2.09	0.99	In test area
	Avg				(60.42)	(5.8)	(12,200)	(1.95)	(0.99)	
	CLBB-8L-6	0.048	0.990	-65	(99.30)	---	---	1.50	---	In test area

* Nominal face sheet thickness based on 0.006 inch per ply
** Strain gage values or extrapolated from strain gage values
***Predicted value (Refer to section V.)

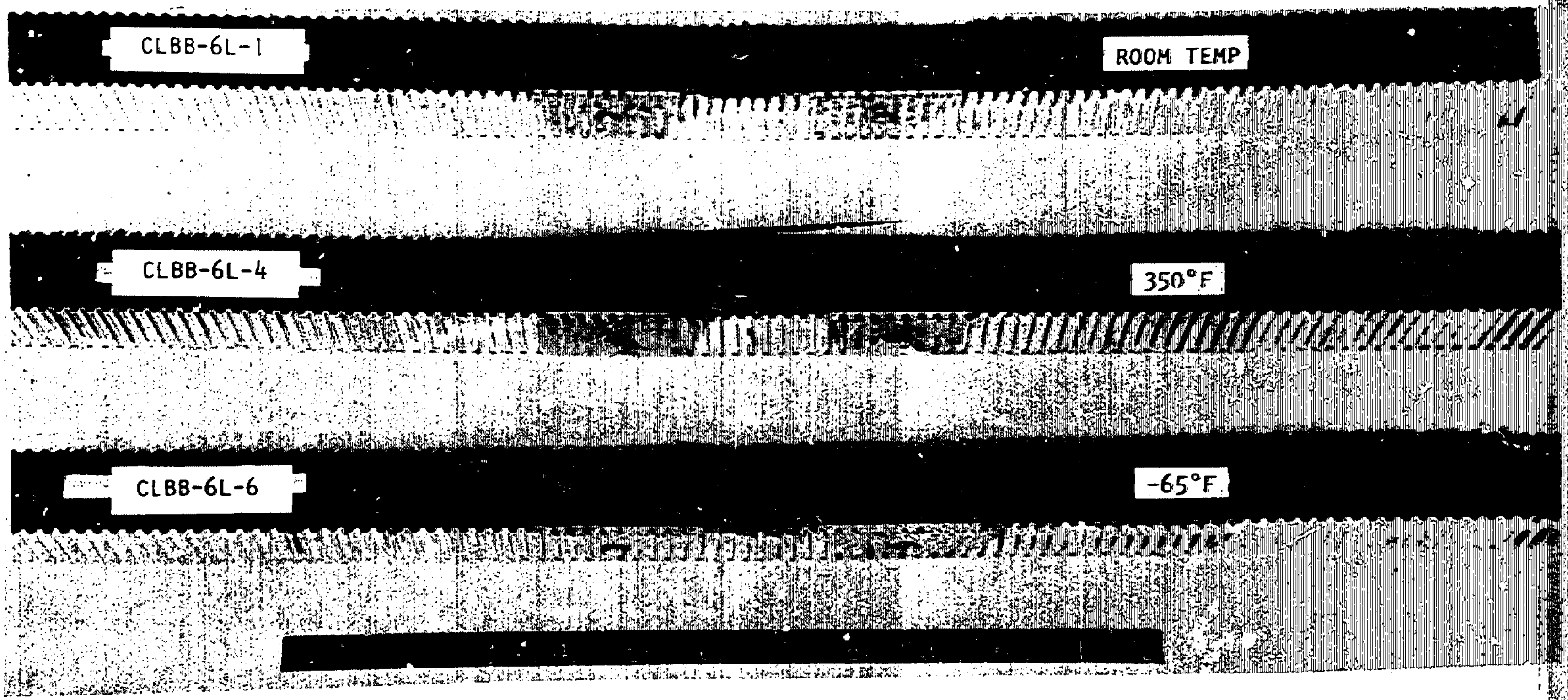


Figure 70. Failed $[0/\pm45]_S$ Crossplied Compression Bending Beam Specimens - Type AS/3002 - Batch, Graphite/Epoxy

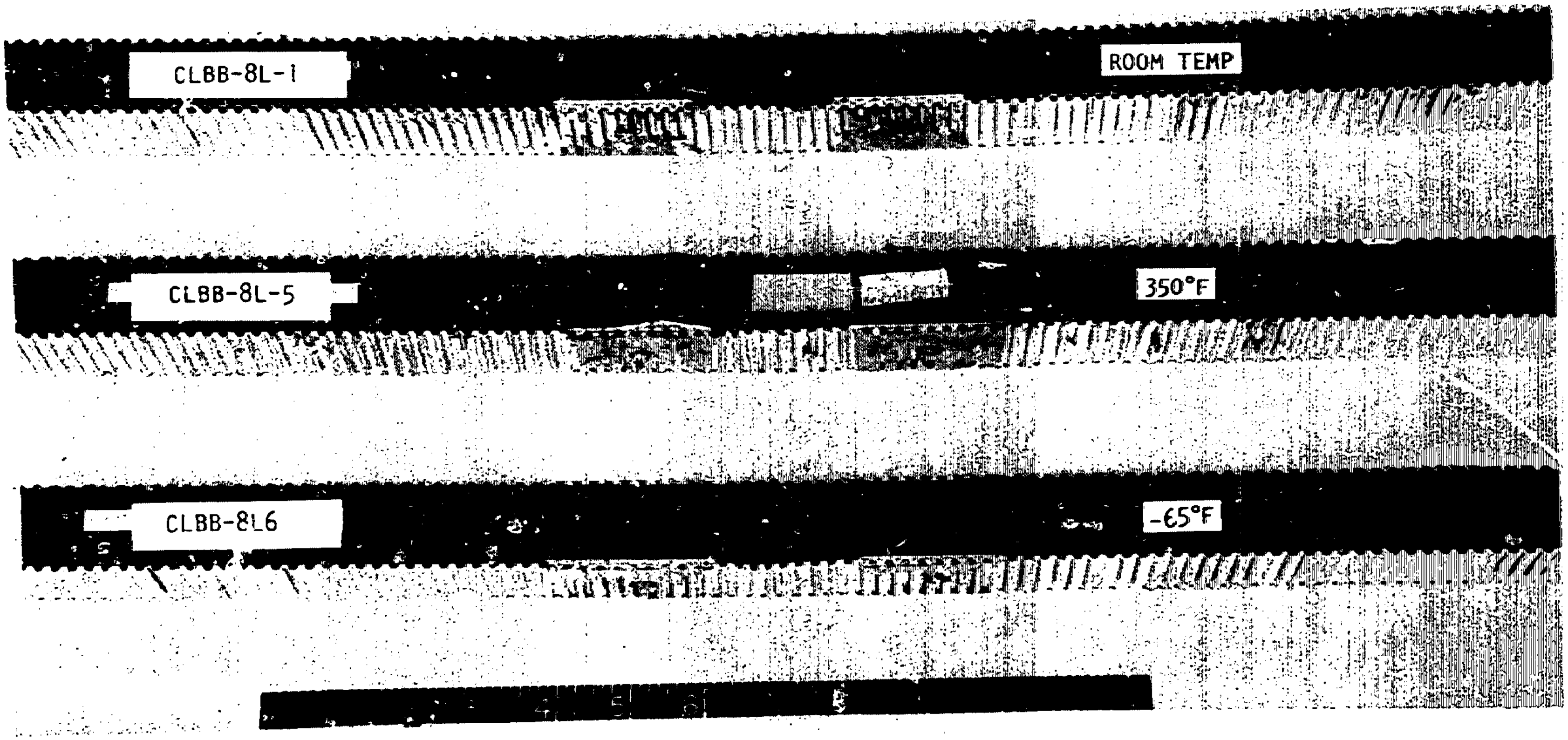


Figure 71. Failed $[0/\pm45/90]_S$ Crossplied Compression Bending Beam Specimens - Type AS/3002 - Batch, Graphite/Epoxy

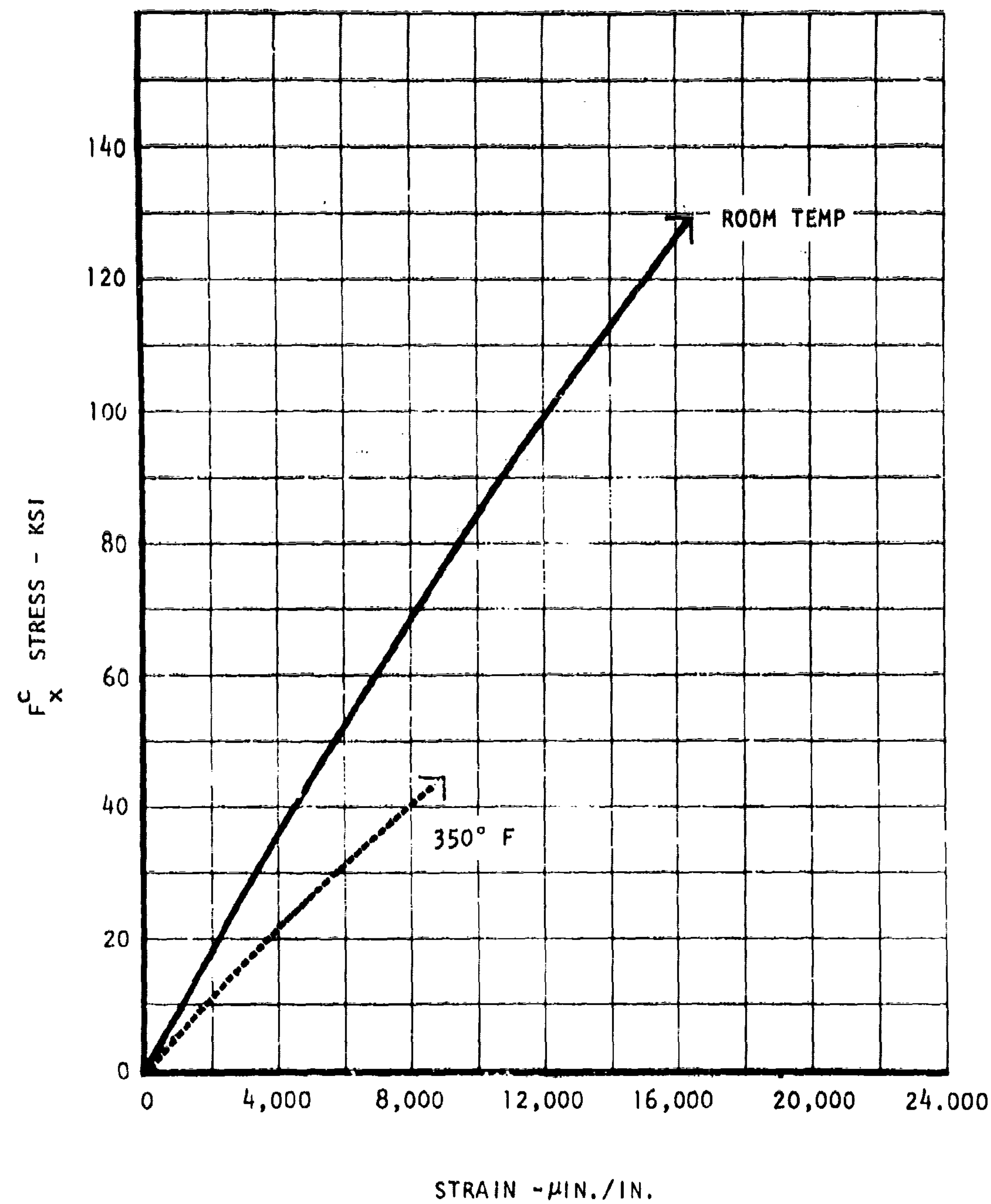


Figure 72. Compression Bending Beam Stress Strain Curves - $[0/\pm45]_S$ Graphite/ Epoxy Laminates - Type AS/3002 - Batch, Room Temperature and 350°F

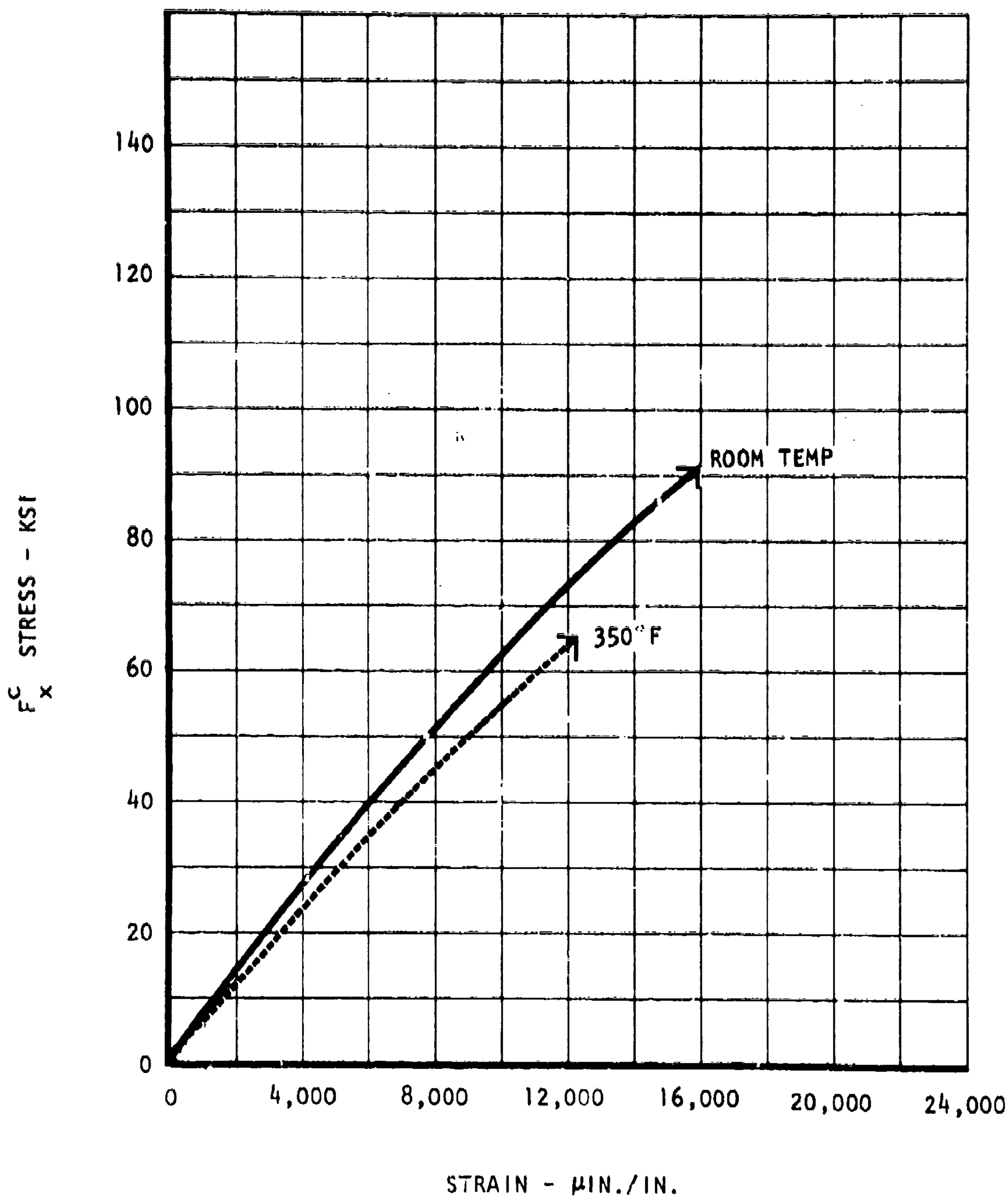


Figure 73. Compression Bending Beam Stress Strain Curves - $[0/\pm45/90]_S$ Graphite/Epoxy Laminates - Type AS/3002 - Batch, Room Temperature and 350°F

TABLE XXIV. CROSSPLIED GRAPHITE/EPOXY COMPRESSION DATA (TYPE A/3002 BATCH - UNTREATED FIBER)

Test Orientation	Specimen No.	Thickness (In.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus E (Msi)	Ultimate Strain (μ in./in.)	Test/Predicted* Strength
$[0/\pm 45/90]_S$	EC-8L-1	0.048	RT	54.6	--	--	0.827
Edgewise	EC-8L-2	0.048	RT	51.1	--	--	0.774
compression	EC-8L-4	0.048	RT	55.9	--	--	(0.817)
sandwich	Avg			(53.9)			
8 plies	EC-8L-3	0.048	350	40.7	--	--	1.313
	EC-8L-5	0.048	350	52.8	--	--	1.703
Load - CL	EC-8L-6	0.048	350	48.2	--	--	1.555
	Avg			(47.3)			(1.526)

NOTE CL = longitudinal compression
* Predicted value (Refer to section V.)

In-Plane Shear Properties

Treated Graphite Fiber Laminates (Type AS/3002)

Room temperature, -65° F, and 350° F rail shear tests for $[0/\pm45]_S$, $[0/\pm45/90]_S$, and $[\pm45]_{2S}$ graphite/epoxy laminates were run to determine in-plane shear modulus and strength values, and the data are presented in table XXV. Typical failed specimens are shown in figures 74, 75, and 76, while room temperature and 350° F shear stress-strain curves for the three orientations are presented in figures 77, 78, and 79.

The strength values shown in table XXV were generally less than predicted, (average of 62 percent of predicted). The modulus values, although less than expected for the $[\pm45]$ orientation, averaged 96 percent of predicted for the three orientations tested: $[0/\pm45]$, $[0/\pm45/90]$, and $[\pm45]$. Analytical shear buckling checks of the test specimen configurations at room temperature were made to insure that the in-plane shear strengths were not affected by a plate buckling mode of failure. For the analysis, the following assumptions were made: effective plate width of 2 inches, simply supported edges or fixed edges, and $a/b = \infty$. The pertinent equations used were obtained from table 4.3.2.I of reference 1. The elastic constants were obtained from section V.

Table XXVI summarizes the calculated buckling values, predicted strengths, and average test values attained. The table shows that, if the effective width, b, of 2 inches is valid, the less-than-expected rail shear strengths can be attributed to a buckling failure mode rather than a ultimate strength failure. Examination of the test setup (figure 47), however, shows that the test specimen unsupported width, b, was about 1 inch, rather than the assumed 2 inches. This precluded the buckling failure mode; however, a spot check of rail shear specimens was initiated (table XXVII) in which the laminate thicknesses were increased or stabilized with honeycomb core to preclude buckling failure even for a 2-inch effective width panel.

Table XXVII summarizes the rerun rail shear tests in which thicker laminates, $[0/\pm45]_{2S}$, and $[0/\pm45/90]_{2S}$, as well as a honeycomb sandwich $[\pm45]_S$ face sheet specimen configurations were tested at room temperature and 350°F. Figures 80, 81, and 82 present typical failed specimen photographs. The specimens run without strain gages were inadvertently tested with inadequate torque on the test fixture bolts. The means of transferring the test machine load to the specimen is basically as "friction load transfer" rather than "bolt bearing." Therefore, the -3 specimen tests were considered invalid, with figure 81 showing failures at the attachments rather then the test section. The strain-gaged room temperature and 350°F rail shear generally yielded expected shear moduli and strengths except for the $[\pm45]_S$ orientation, which had less than predicted strength values. However, the rail shear specimen

TABLE XXV. CROSSPLIED GRAPHITE/EPOXY RAIL SHEAR DATA - IN-PLANE SHEAR (TYPE AS/3002 BATCH)

Test Orientation	Specimen No.	Thickness* (In.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus E (Msi)**	Ultimate Strain γ (μ in./in.)	Test/Predicted*** Strength	Test/Predicted*** Modulus
$[0/\pm45]_S$	RS-6L-1	0.036	RT	25.90			0.719	
	RS-6L-2	0.036	RT	20.47			0.569	
6 plies	RS-6L-3	0.036	RT	17.65	4.18	6.300	0.490	1.286
	Avg			(21.34)			(0.592)	
	RS-6L-4	0.036	350	14.74			0.641	
	RS-6L-6	0.036	350	15.74	3.43	5,500	0.684	1.203
	Avg			(15.24)			(0.662)	
	RS-6L-5	0.036	-65	17.61			0.489	
$[0/\pm45/90]_S$	RS-8L-1	0.048	RT	24.00			0.857	
	RS-8L-2	0.048	RT	24.96			0.891	
8 plies	RS-8L-3	0.048	RT	22.63	2.33	12,300	0.808	0.896
	Avg			(23.86)			(0.852)	
	RS-8L-4	0.048	350	18.38			1.021	
	RS-8L-6	0.048	350	17.51	2.63	7,800	0.973	1.195
	AVG			(17.95)			(0.997)	
	RS-8L-5	0.048	-65	19.41			0.693	
$[\pm45]_{2S}$	RS-8AL-1	0.048	RT	18.71			0.374	
	RS-8AL-2	0.048	RT	22.18			0.444	
8 plies	RS-8AL-3	0.048	RT	16.47	3.16	6,250	0.329	0.702
	Avg			(19.12)			(0.382)	
	RS-8AL-4	0.048	350	15.42			0.454	
	RS-8AL-6	0.048	350	12.93	2.08	18,000	0.380	0.501
	Avg			(14.18)			(0.417)	
	RS-8AL-5	0.048	-65	20.52			0.410	

* Based on nominal ply, t = 0.006 inch/ply

** Strain gage data

*** Predicted values (Refer to section V.)

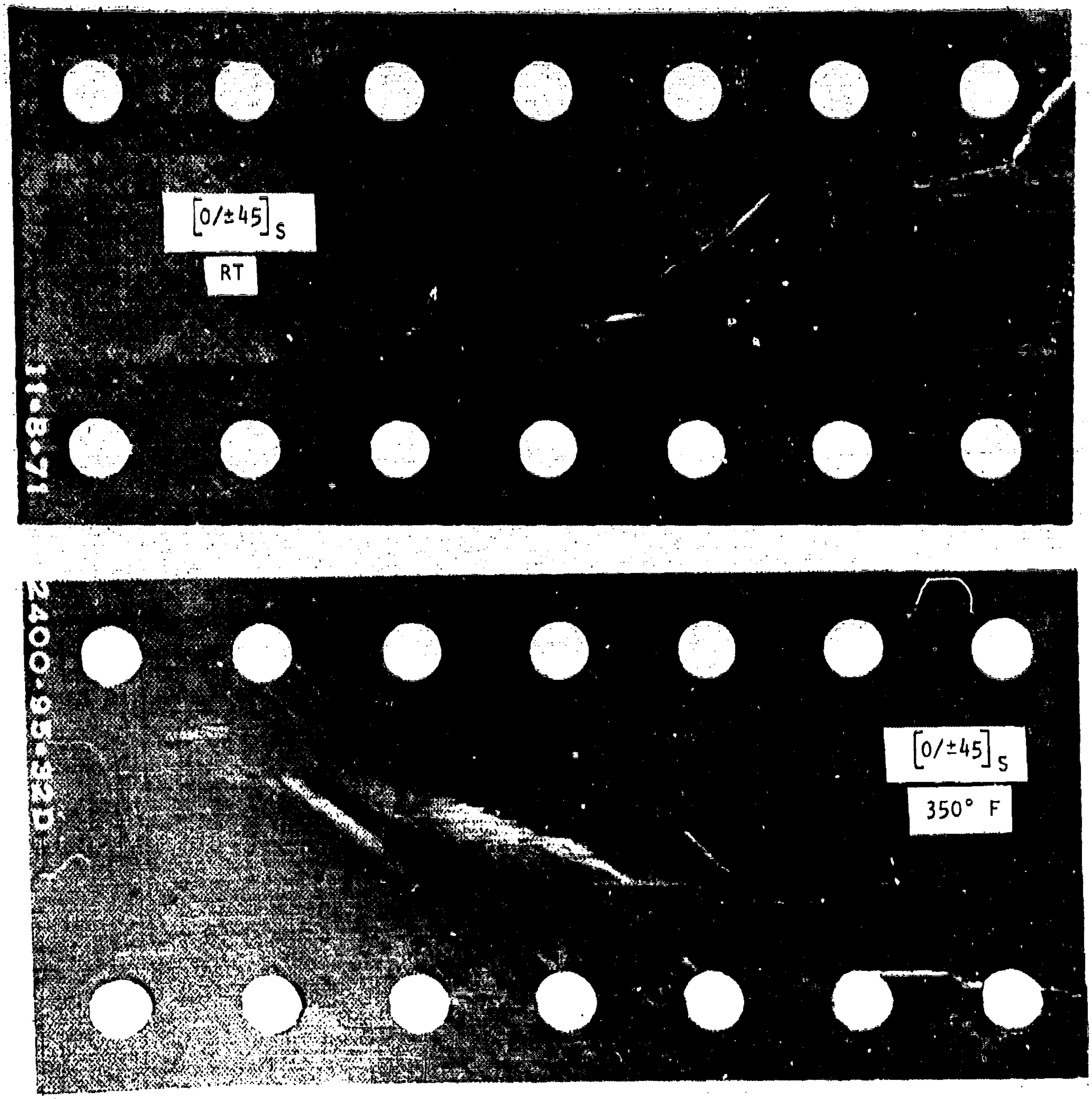


Figure 74. Typical Failed Rail Shear Specimens - Crossplied Graphite/Epoxy, $[0/\pm45]_S$ Orientation, Type AS/3002 - Batch, Room Temperature and 350°F

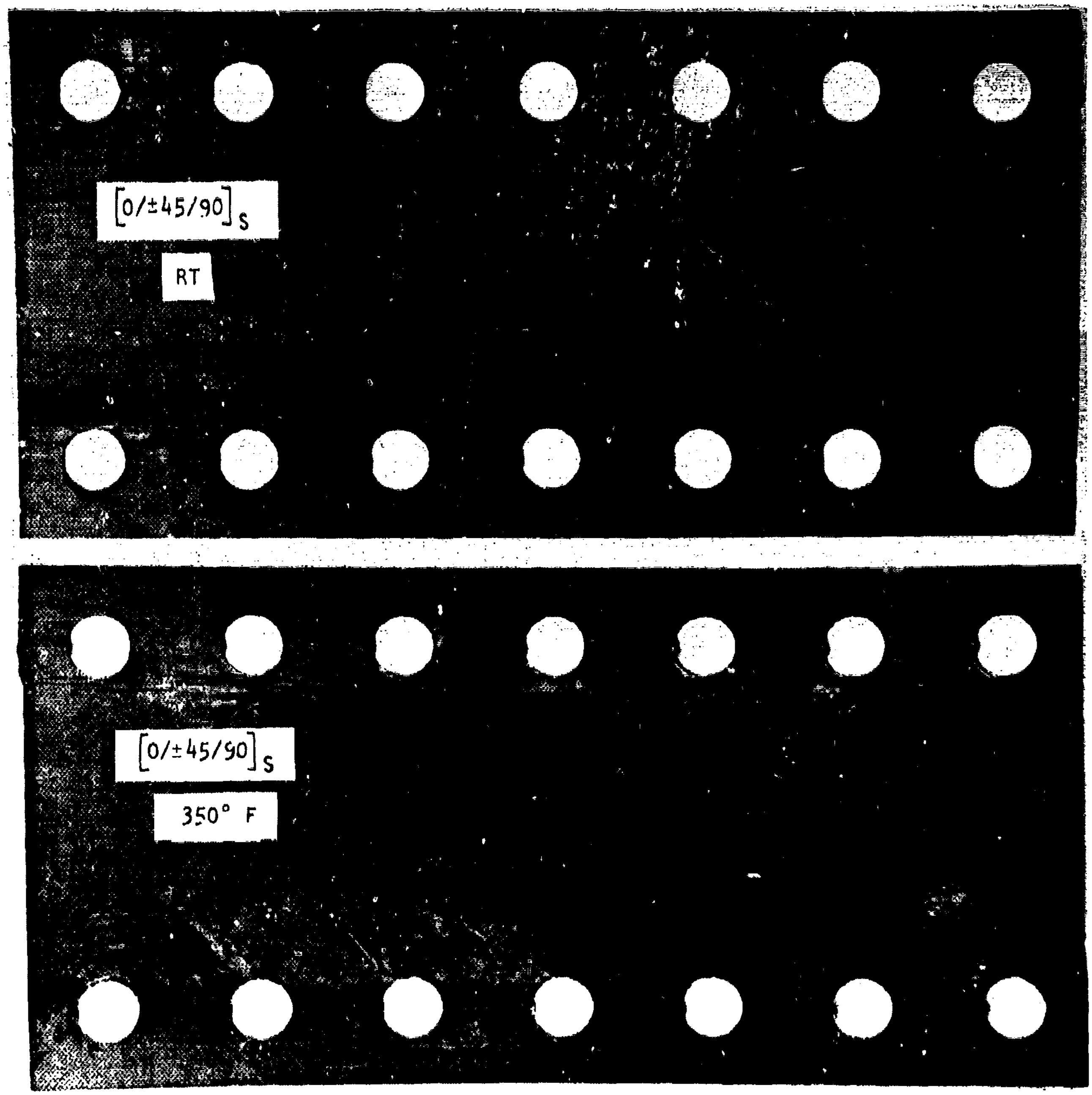


Figure 75. Typical Failed Rail Shear Specimens - Crossplied Graphite/Epoxy, $[0/\pm45/90]_S$ Orientation, Type AS/3002 - Batch, Room Temperature and 350°F

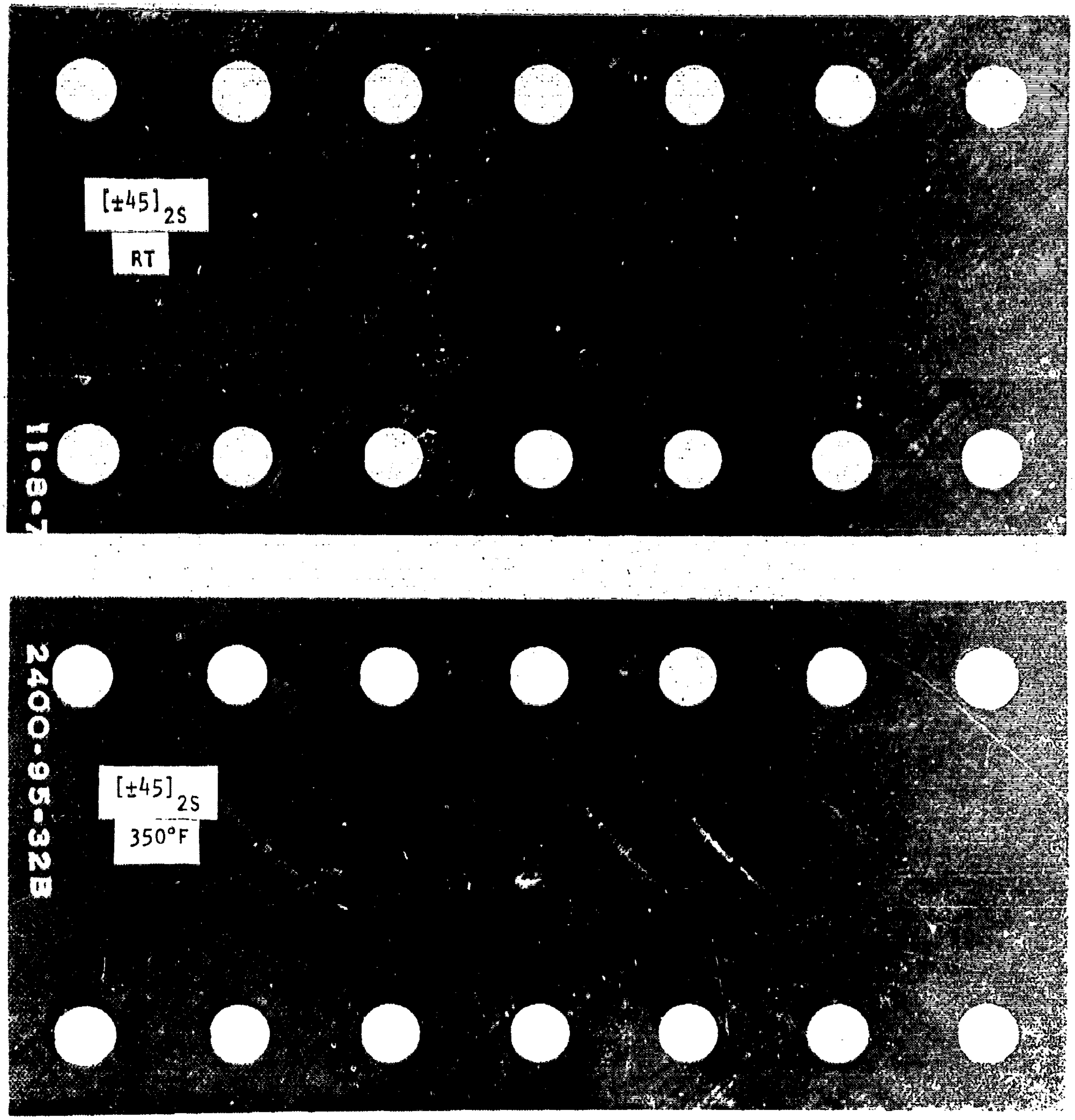


Figure 76. Typical Failed Rail Shear Specimens - Crossplied Graphite/Epoxy, $[\pm 45]_{2S}$ Orientation, Type AS/3002 - Batch, Room Temperature and 350°F

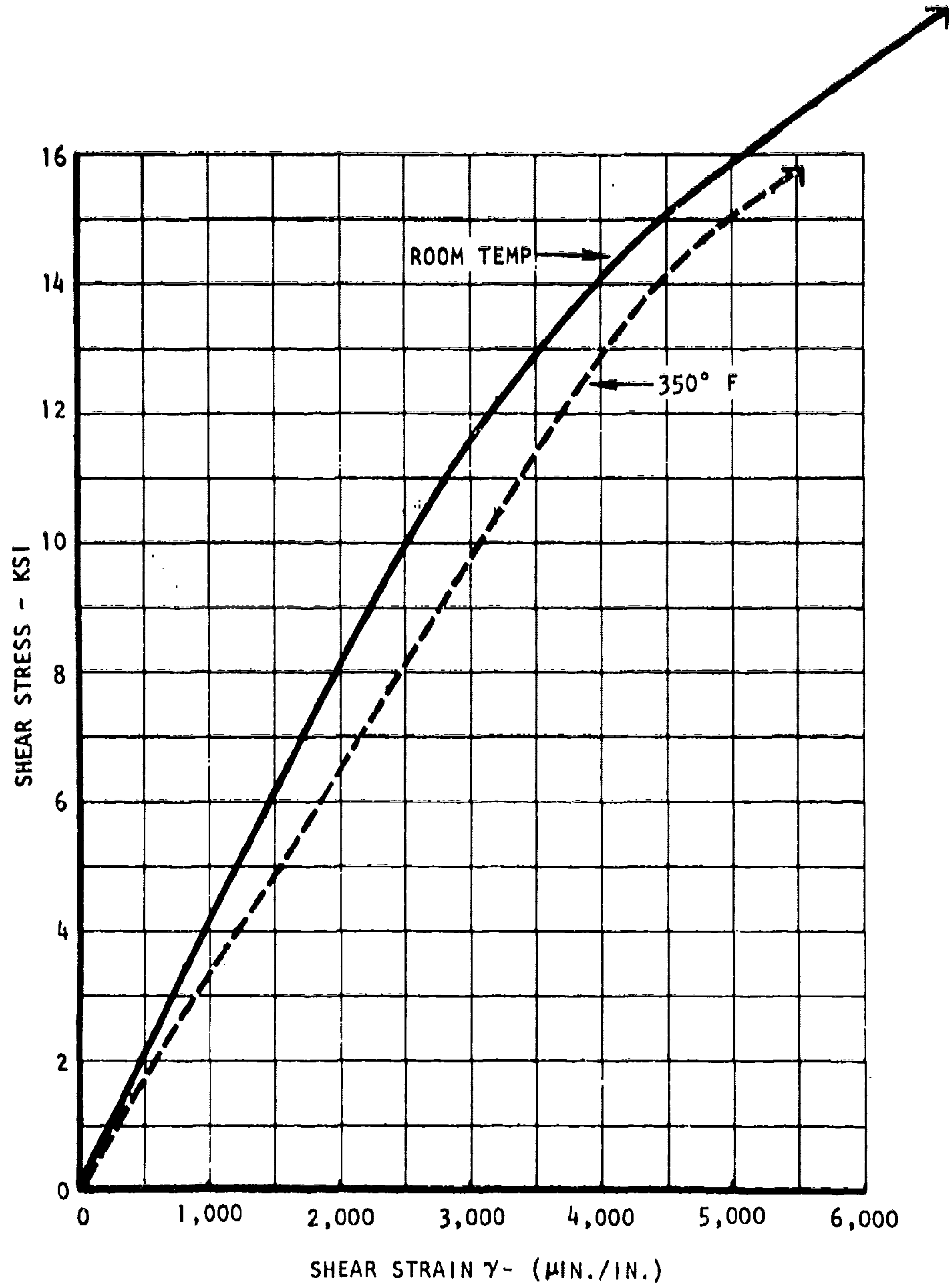


Figure 77. Crossplied $[0/\pm45]_S$ Graphite/Epoxy, Typical Shear Stress-Strain Curves, Type AS/3002 - Batch, Room Temperature and 350°F

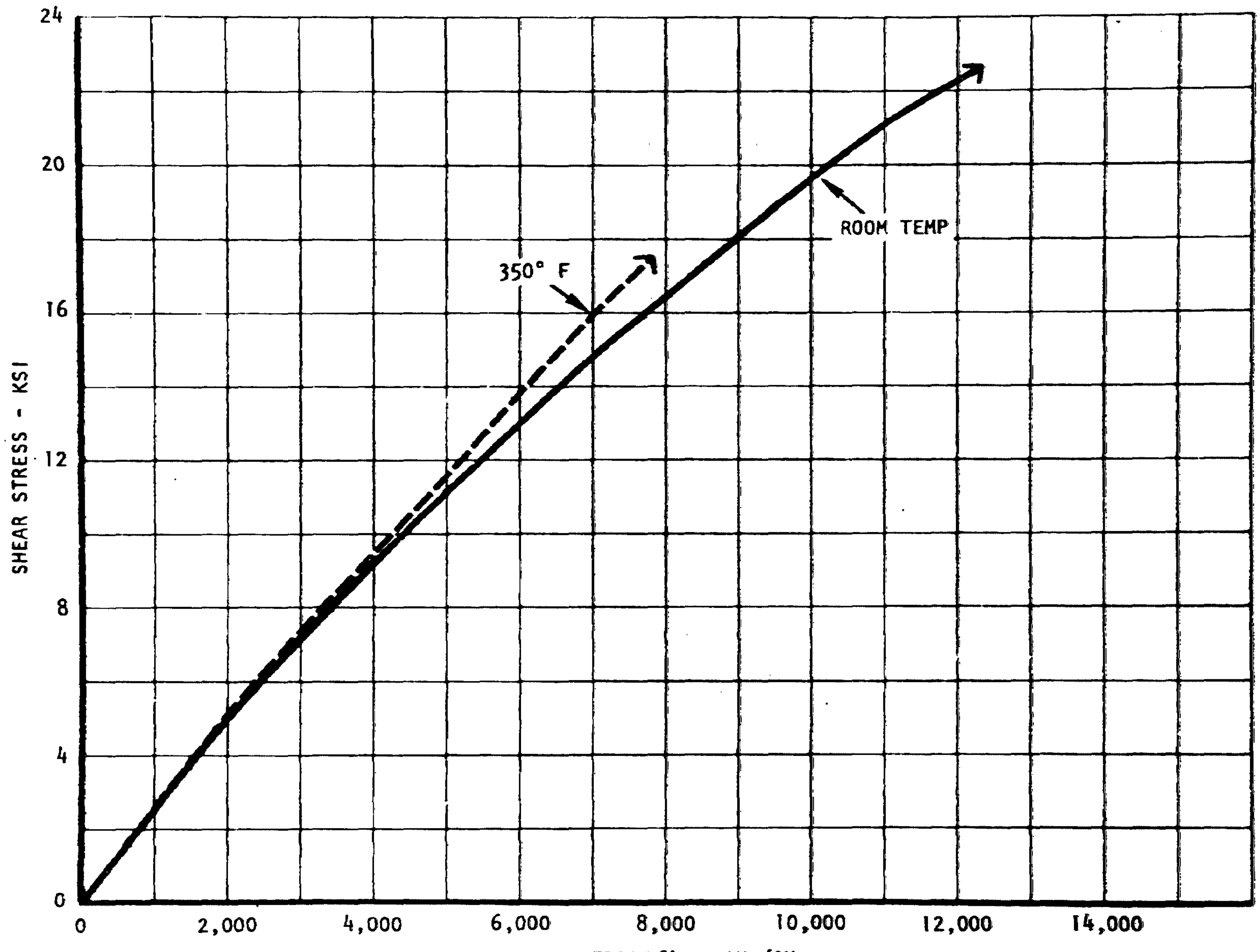


Figure 78. Crossplied $(0/\pm45/90)_S$ Graphite/Epoxy, Typical Shear Stress-Strain Curves, Type AS/3002 - Batch, Room Temperature and 350°F

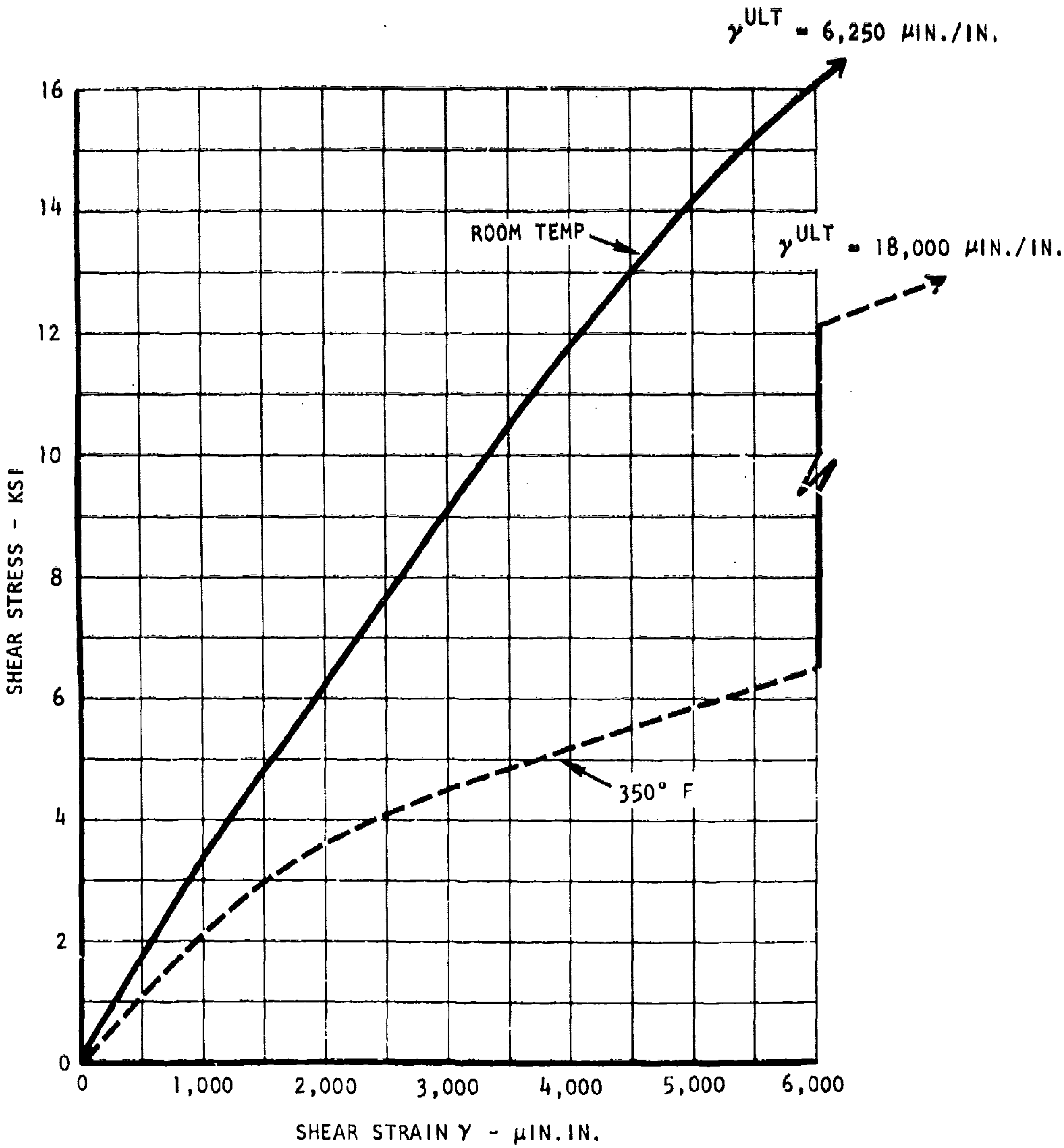


Figure 79. Crossplied [±45] Graphite/Epoxy Typical Shear Stress-Strain Curve, Type AS/3002 - Batch, Room Temperature and 350°F

TABLE XXVI. SHEAR PANEL STABILITY ANALYSIS

Parameters	Orientation		
	$[0/\pm45]_S$	$[0/\pm45/90]_S$	$[\pm45]_{2S}$
t (in.)	0.036	0.048	0.048
$D_{11} = \frac{E_x t^3}{\alpha}$ (1)	36.06	68.85	53.35
$D_{22} = \frac{E_y t^3}{\alpha}$	16.80	68.85	53.35
$D_{12} = \frac{E_x \nu_{yx} t^3}{\alpha}$	11.18	21.34	40.81
$D_{66} = \frac{G_{xy} t^3}{12}$	12.64	23.70	37.80
θ (2)	0.675	1.002	0.458
β (3)	1.0	1.0	1.0
N_{xy} cr (SS) (4) (b = 2 in.)	309	916	956
N_{xy} cr (fixed) (5) (b = 2 in.)	509	1,536	1,556
Predicted strength N_{xy}, ultimate	1,296	1,392	2,400
Test value N_{xy} (avg)	768	1,145	918

(1) $\alpha = 1 - \nu_{xy}\nu_{yx}$

(2) $\theta = \sqrt{D_{11}\,D_{22}} \Big/ \left(D_{12} + 2D_{66}\right)$

(3) $\beta = (2/b)^2$

(4) $N_{xy,\,cr} = \beta \left(D_{11}\,D_{22}^{\,3}\right)^{1/4} \left(8.125 + 5.05/\theta\right)$ for $\theta > 1$

$= \beta\sqrt{D_{22}\left(D_{12} + 2D_{66}\right)} \left(11.7 + 0.532\theta + 0.938\theta^2\right)$ for $\theta < 1$

(5) $N_{xy,\,cr} = \beta \left(D_{11}\,D_{22}^{\,3}\right)^{1/4} \left(15.1 + 7.0/\theta\right)$ for $\theta > 1$

$= \beta\sqrt{D_{22}\left(D_{12} + 2D_{66}\right)} \left(18.6 + 1.65\theta + 1.90\theta^2\right)$ for $\theta < 1$

TABLE XXVII. CROSSPLIED GRAPHITE/EPOXY RAIL SHEAR DATA - IN-PLANE SHEAR (TYPE AS/3002 BATCH - THICKER LAMINATE AND SANDWICH DATA)

Test Orientation	Specimen No.	Thickness (In.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus E (Msi)**	Ultimate Strain γ (μ in./in.)	Test Predicted*** Strength	Test Predicted*** Modulus
$[0/\pm45]_S$	RS-12L-3	0.072	RT	15.43*			0.429*	
	RS-12L-1	0.072	RT	34.94	3.20	12,600	0.971	0.985
12 plies	RS-12L-2	0.072	350	34.79	3.00	12,550	1.513	1.050
$[0/\pm45/90]_{2S}$	RS-16L-3	0.096	RT	19.00*	-	-	0.679*	-
	RS-16L-1	0.096	RT	35.20	2.90	14,650	1.257	1.115
16 plies	RS-16L-2	0.096	350	33.59	2.70	14,600	1.866	1.227
$[\pm45]_S$ Sandwich	RS-4A-3	0.024	RT	18.51*			0.370*	
	RS-4A-1	0.024	RT	28.59	4.88	6,750	0.572	1.190
4 plies****	RS-4A-2	0.024	350	22.58	4.60	7,700	0.674	1.211

* Invalid data - tested with inadequate torque on bolts
** Strain gage data
*** Predicted values (Refer to section V.)
**** 4 plies per face sheet

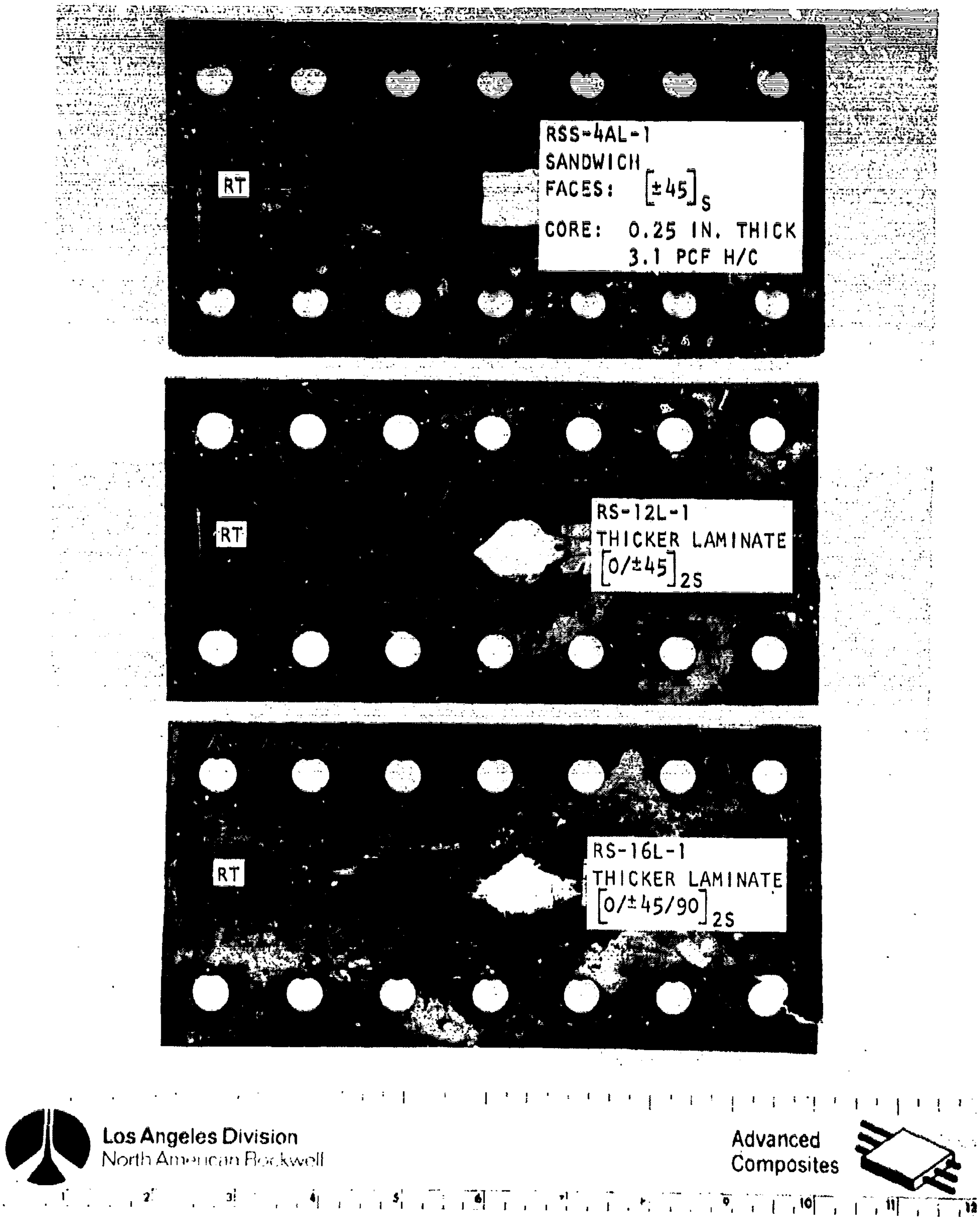


Figure 80. Typical Failed Rail Shear Specimens - Crossplied Graphite/Epoxy, Sandwich and Thicker Laminate Configurations, Room Temperature, Adequately Torqued Bolts

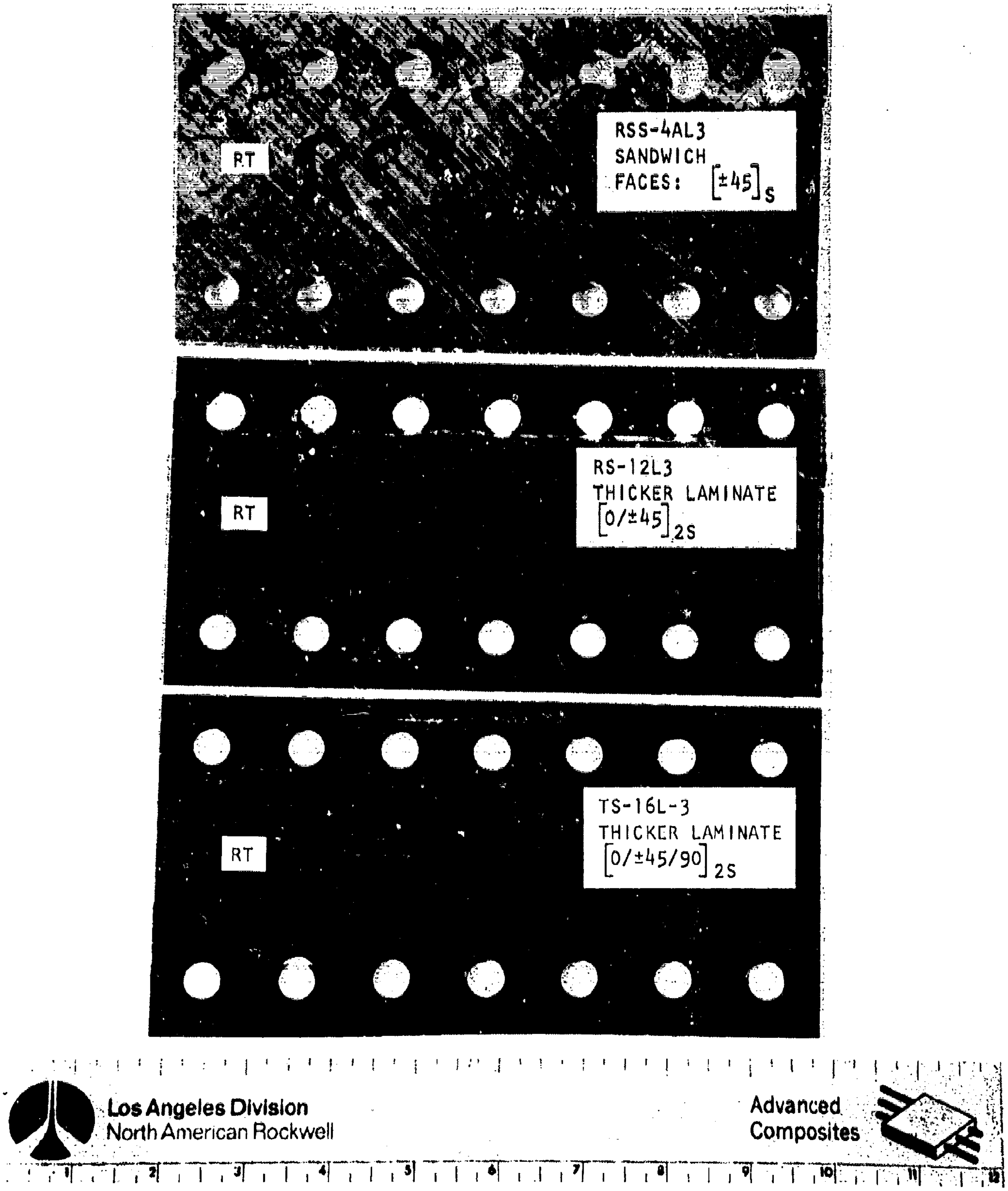


Figure 81. Typical Failed Rail Shear Specimens - Crossplied Graphite/Epoxy, Sandwich and Thicker Laminate Configurations, Room Temperature, Inadequately Torqued Bolts

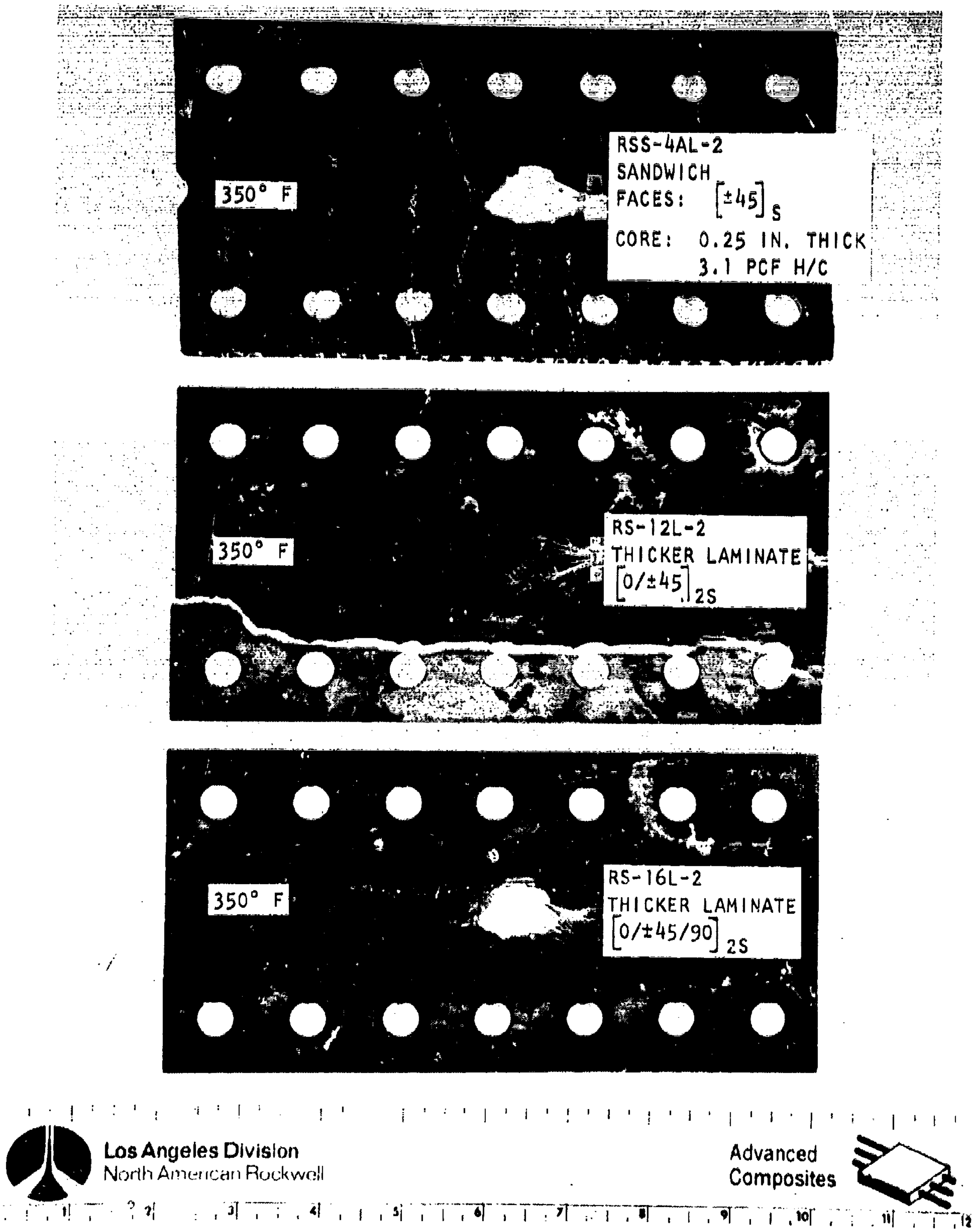


Figure 82. Typical Failed Rail Shear Specimens - Crossplied Graphite/Exroxy, Sandwich and Thicker Laminate Configurations, 350°F

has not attained predicted strengths for the [±45] orientation throughout the industry, and the method of obtaining a realistic value is by using the results of an axially loaded tension coupon and the AC3 point stress analysis computer program (appendix 2.B of reference 8).

Using the lamination theory presented in appendix A of reference 1, a computer program, designated "AC3 Point Stress Analysis," has been developed for presentation in the Third Edition of the Design Guide. This program was used to evaluate lamina stresses for the $[\pm 45]_{2S}$ orientation case. Results are presented in table XXVIII. Load condition 1 is the case of axial tension loading, N_x = 1262 lb/in., which represents the average room temperature tensile strength level attained from the crossplied $[\pm 45]_{2S}$ tension coupon data reported in table XIX. Examination of the lamina stresses shows that a maximum shear stress τ_{LT} = 13,146 psi was attained indicating that the design F_{LT}^{su} = 10,000 psi was satisfactorily exceeded. Load condition 2 is the assumed in-plane shear loading case of N_{xy} = 2,400 lb/in. which represents the ultimate design strength capability of F_{xy}^{su} = 50,000 psi for [±45] orientation. The limiting lamina stress level is τ_{LT} = 7,467 psi which corresponds to F_T^{tu} = 7.5 ksi specified in section V.

Therefore, it is concluded that the rail shear test for [±45] orientation provides lower strength levels than predicted by lamination theory and that these lower values are due to the inherent stress concentrations present in this type of test. The design values will be based on the lamination theory results.

Typical shear stress-strain curves at room temperature and 350°F are shown in Figures 83, 84, and 85 for laminate orientations $[0/\pm 45]_{2S}$ $[0/\pm 45/90]_{2S}$, and $[\pm 45]_S$ respectively.

Untreated Graphite Fiber Laminates (Type A/3002)

Table XXIX presents rail shear test data for room temperature, 350°F, and -65°F tests run on $[0/\pm 45/90]_S$ graphite/epoxy Type A/3002 batch laminates. The average strengths exceeded predicted values by 37 to 77 percent, while the average in-plane shear moduli were about as expected (within 7 percent).

Figures 86 and 87 present typical room temperature and 350°F failed test specimen photographs, while figure 88 shows typical room and elevated temperature shear stress-strain curves.

TABLE XXVIII. POINT STRESS ANALYSIS - AC3 COMPUTER PROGRAM

Orientation: $[\pm 45]_{2S}$

Material: Type AS/3002

Lamina properties: E_L = 17,000,000 psi, E_T = 1,700,000 psi, G_{TL} = 650,000 psi, ν_{LT} = 0.2100

Laminate Layup				Laminate Elastic Properties $\overline{Q}_{ij}$			
Layer	Matl	Theta	Thickness	Layer 1	5,524,993	4,224,989	3,841,937
1	1	45	0.006		4,224,989	5,524,990	3,841,936
2	1	-45	0.006		3,841,937	3,841,936	4,516,405
3	1	45	0.006	Layer 2	5,524,993	4,224,989	-3,841,937
4	1	-45	0.006		4,224,989	5,524,990	-3,841,936
5	1	-45	0.006		-3,841,937	-3,841,936	4,516,405
6	1	45	0.006				
7	1	-45	0.006				
8	1	45	0.006				

Laminate	Load Condition 1		Load Condition 2	
Strains / Stresses	N_x = 1,262 ϵ_y = -0.00876386	ϵ_x = 0.01146044 γ_{xy} = 0.00000000	N_{xy} = 2400 ϵ_x = 0.00000000	γ_{xy} = 0.01107976 ϵ_y = 0.00000000
Layer 1	σ_x = 26,292 σ_y = 0 τ_{xy} = 10,360	σ_L = 23,506 σ_T = 2,786 τ_{LT} = -13,146	σ_x = 42,533 σ_y = 42,533 τ_{xy} = 50,000	σ_L = 92,533 σ_T = -7,467 τ_{LT} = 0
Layer 2	σ_x = 26,292 σ_y = 0 τ_{xy} = -10,360	σ_L = 23,506 σ_T = 2,786 τ_{LT} = 13,146	σ_x = -42,533 σ_y = -42,533 τ_{xy} = 50,000	σ_L = -92,533 σ_T = 7,467 τ_{LT} = 0

TABLE XXIX. CROSSPLIED GRAPHITE/EPOXY IN-PLANE SHEAR DATA (TYPE A/3002 BATCH - UNTREATED FIBER)

Test Orientation	Specimen No.	Thickness (In.)	Temp (°F)	Ultimate Stress (Ksi)	Modulus E (Msi)*	Ultimate Strain γ (μ in/in.)	Test Predicted** Strength	Test Predicted** Modulus
$[0/\pm45/90]_S$	RS-8L-1	0.046	RT	34.9	2.43	21,000	1.246	0.935
Rail shear	RS-8L-2	0.046	RT	41.7			1.489	
8 plies	Avg			(38.3)			(1.368)	
	RS-8L-3	0.046	350	31.5	2.29	15,700	1.750	1.041
	RS-8L-4	0.047	350	32.3			1.794	
	Avg			(31.9)			(1.772)	
	RS-8L-5	0.047	-65	42.9			1.532	
	RS-8L-6	0.047	-65	35.8			1.279	
	Avg			(39.3)			(1.404)	

* Strain gage data
** Predicted value (Refer to section V.)

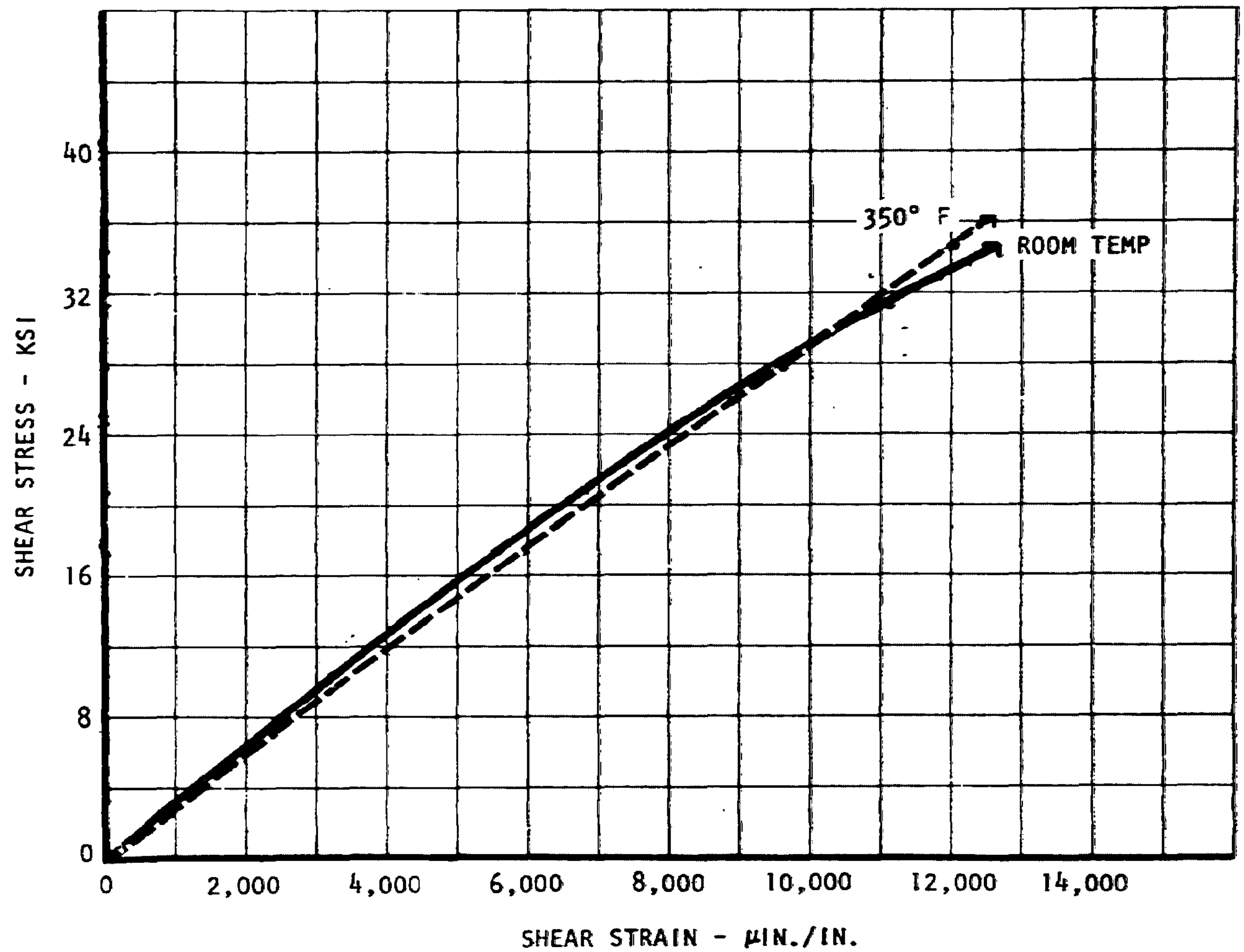


Figure 83. Crossplied $[0/\pm 45]_{2S}$ Graphite/Epoxy, Typical Shear Stress-Strain Curves, Type AS/3002 - Batch, Room Temperature and 350°F

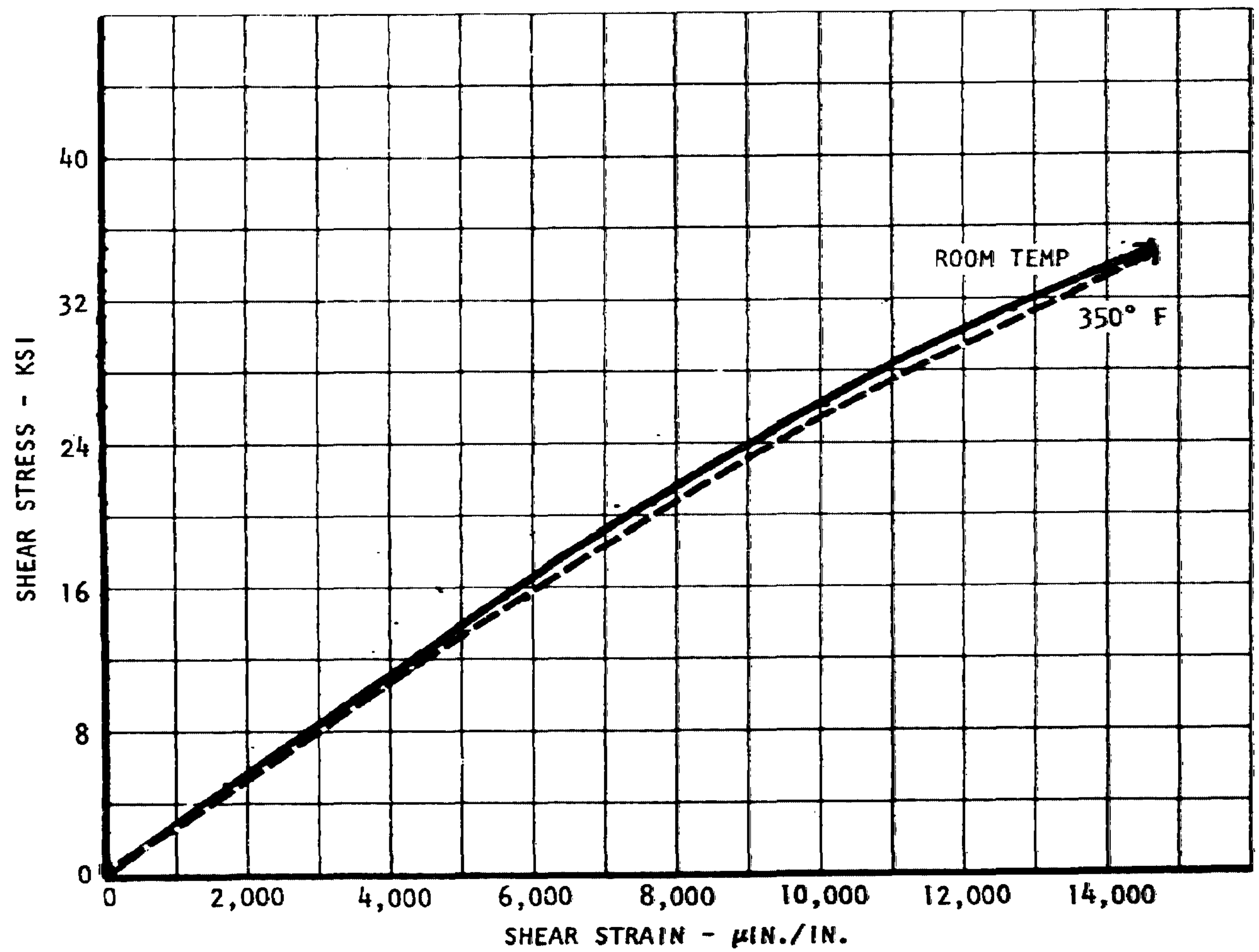


Figure 84. Crossplied $[0/\pm45/90]_{2S}$ Graphite/Epoxy, Typical Shear Stress-Strain Curves, Type AS/3002 - Batch, Room Temperature and 350°F

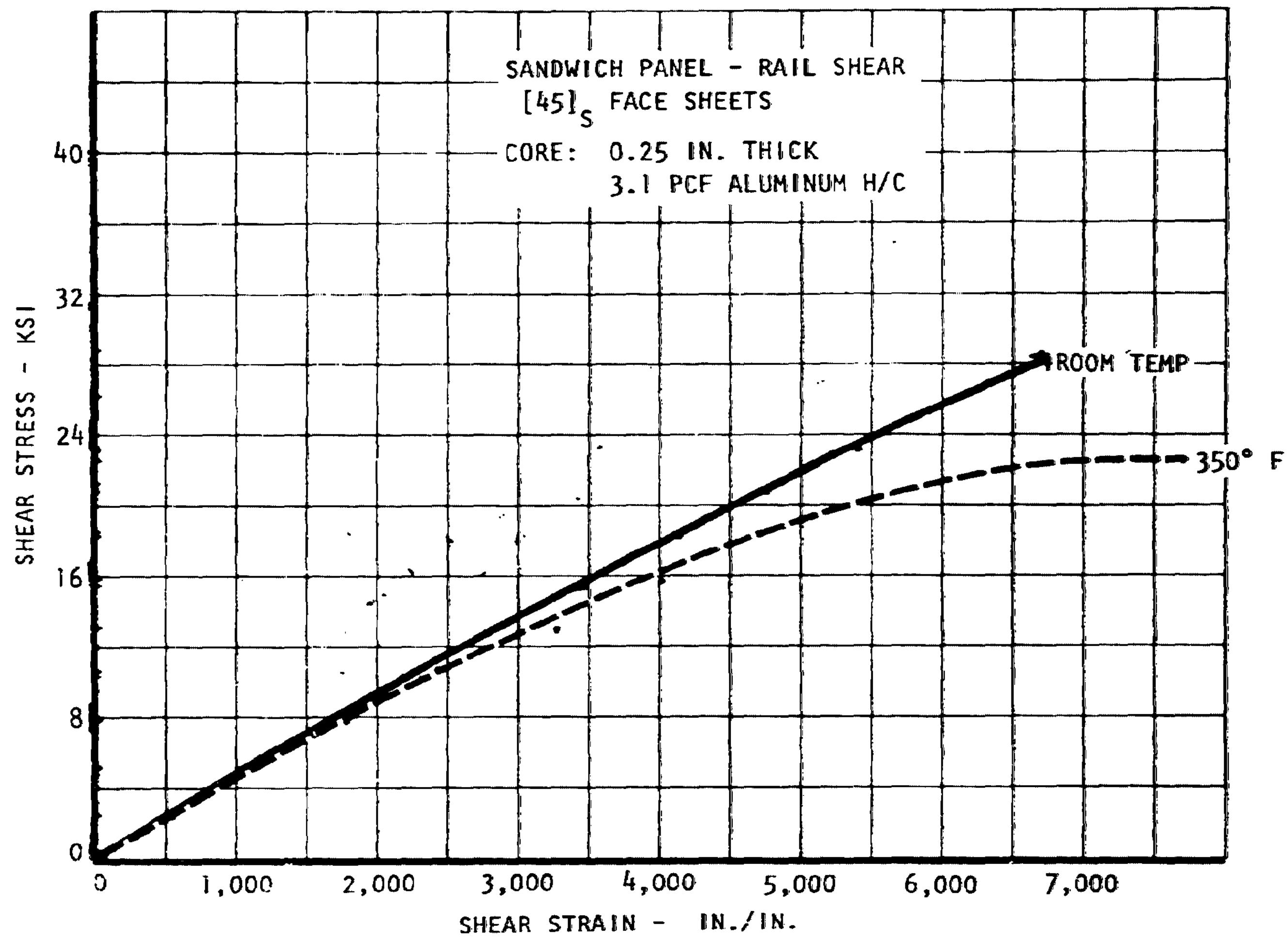


Figure 85. Crossplied $[45]_S$ Graphite/Epoxy, Typical Shear Stress-Strain Curves, Type AS/3002 - Batch, Room Temperature and 350°F

GRAPHITE EPOXY
TYPE A/3002 BATCH
UNTREATED FIBER

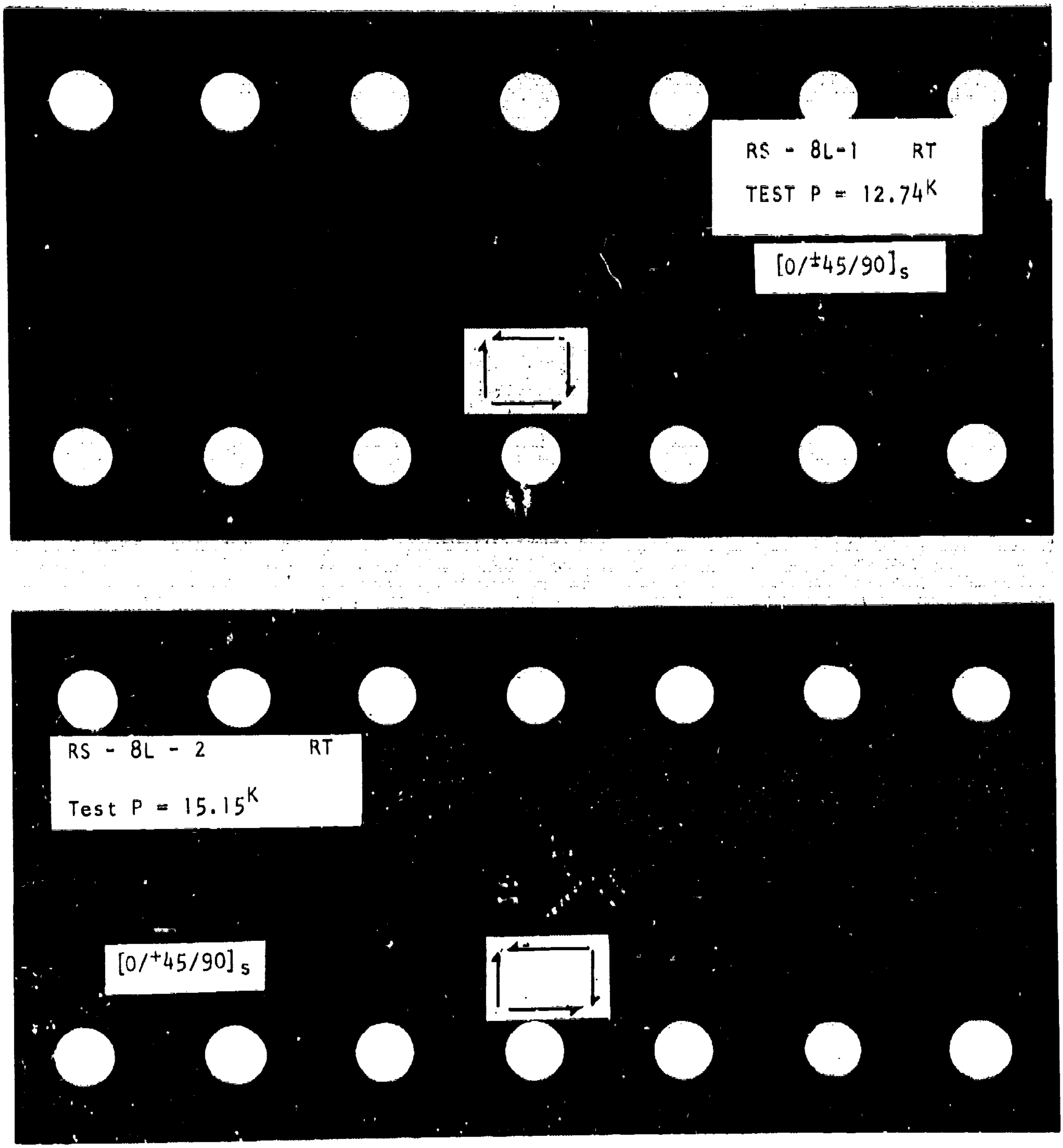


Figure 86. Failed Rail Shear Specimens - Crossply $[0/\pm45/90]_S$ - Room Temperature

GRAPHITE EPOXY
TYPE A/3002 BATCH
UNTREATED FIBER

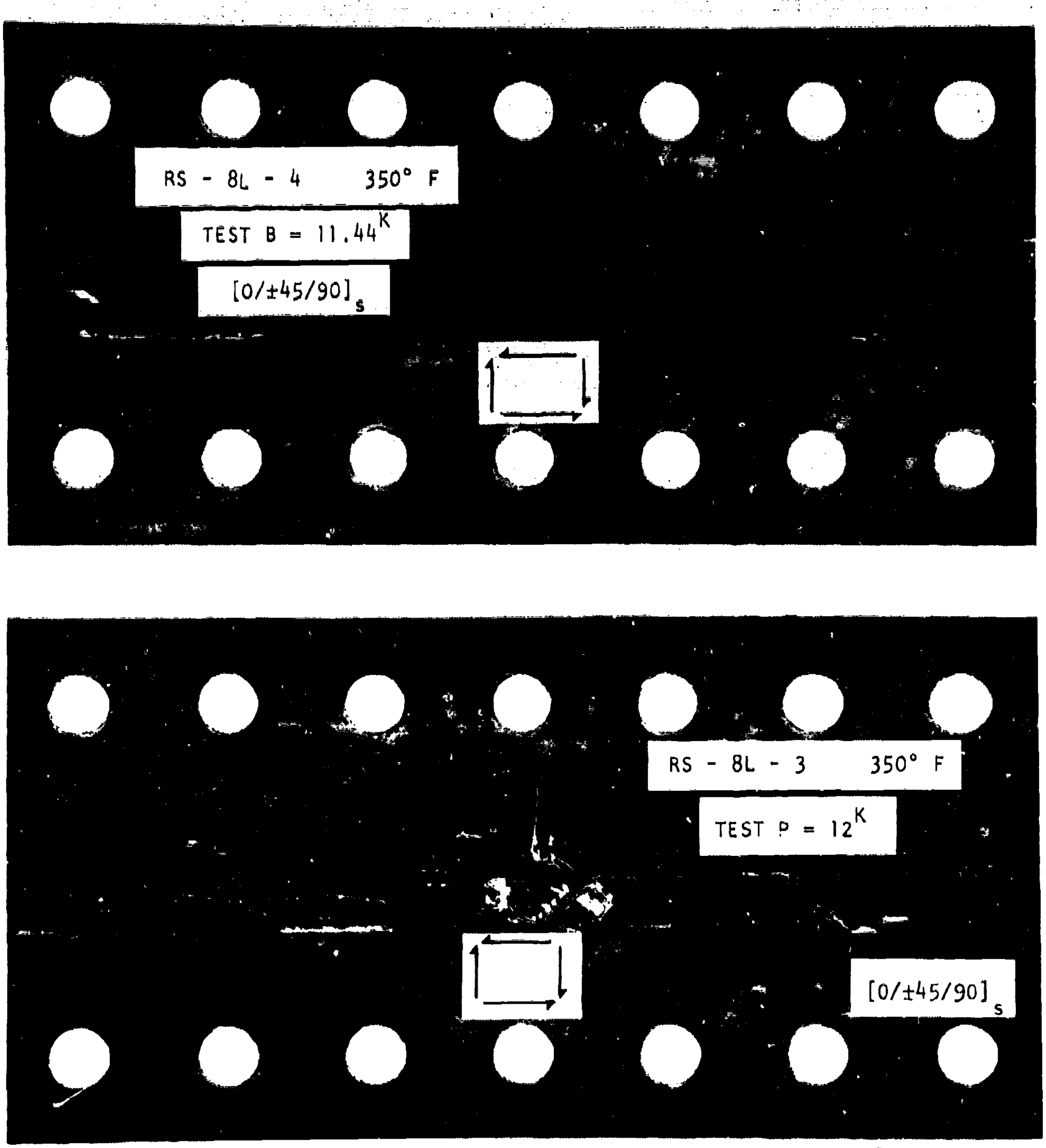


Figure 87. Failed Rail Shear Specimens - Crossply $[0/\pm45/90]_S$ - Elevated Temperature Test, 350°F

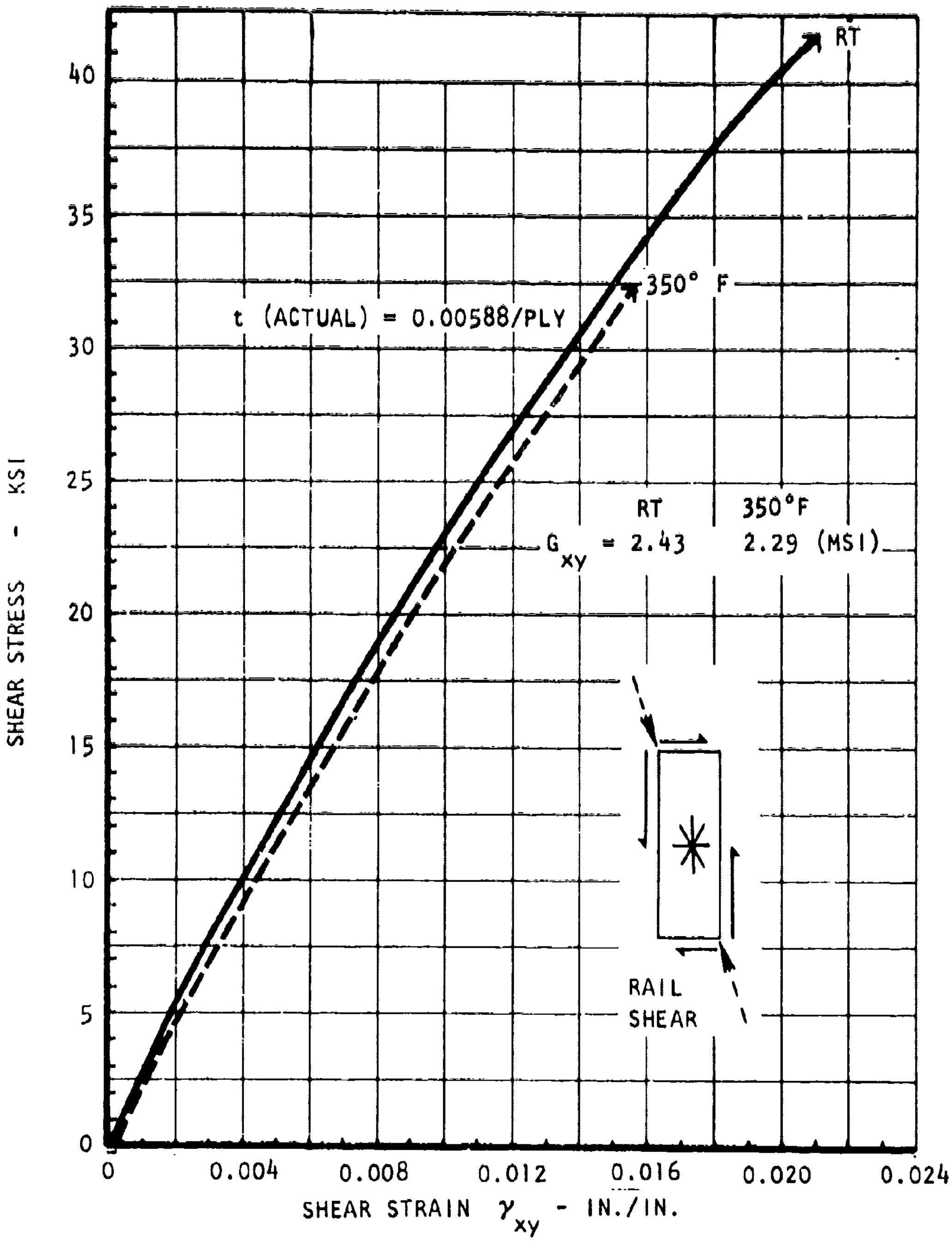


Figure 88. Graphite/Epoxy - In-Plane Shear Stress-Strain Properties - Crossply $[0/\pm45/90]_S$ - Type A/3002 Batch - Untreated Fiber

Interlaminar Shear Data

Crossplied interlaminar shear specimen test data for various laminate orientations are summarized in table XXX based on the standard quality control test using a short beam span of 0.40 inch.* Six symmetric laminate orientations of $[0/\pm45]_{2S}$, $[90/\pm45]_{2S}$, $[\pm45]_{3S}$, $[0/\pm45]_{2S}$, $[90/\pm45]_{2S}$, and $[0/\pm45/90]_{2S}$ were tested at room temperature, 350°F and -65°F. The symmetric layup requirement necessitated the use of 12-ply and 16-ply laminates which differs from the nominal 13-ply unidirectional quality control short beam specimen.

A comparison of interlaminar shear properties of crossplied laminates (table XXX) with the conventional unidirectional short beam shear data (table XV) can be summarized as follows:

1. At room temperature, values ranged from 32 percent $[90/\pm45]_{2S}$ to 67 percent $[90_2/\pm45]_{2S}$ of unidirectional data with an average of 47 percent.

2. At 350°F, values ranged from 41 percent $[\pm45]_{3S}$ to 83 percent $[90_2/\pm45]_{2S}$ of unidirectional data with an average of 62 percent.

3. At -65°F, values ranged from 23 percent $[\pm45]_{3S}$ to 59 percent $[0/\pm45/90]_{2S}$ of unidirectional data with an average of 35 percent.

4. The lower values for the crossplied laminates indicate that the $[\pm45]$ or [90] ply midsurface interlaminar shear strengths are less than the conventional unidirectional [0] based on short beam tests. In all cases, however, the interlaminar shear strengths were greater than the reported bonded lap joint shear strengths in tables XXXIII and XXXIV.

Figure 89 presents a plot of interlaminar shear strength versus temperature for various graphite/epoxy laminate orientations.

*The last column of table XXX presents the adjusted interlaminar shear stress which accounts for the different ply or layer elastic moduli values and lamination sequence.

TABLE XXX. CROSSPLIED GRAPHITE/EPOXY INTERLAMINAR SHEAR DATA
(TYPE AS/3002 BATCH)

Test Orientation	Specimen No.	Thickness (in.)	Temp (°F)	Stress F^{isu} (Ksi)	Stress Avg (Ksi)	Adjusted F^{isu*} (Ksi)
$[0/\pm45]_{2S}$	ILS-12L-1	0.0726	RT	11.85		10.74
	ILS-12L-2	0.0710	RT	10.00		9.07
12 plies	ILS-12L-3	0.0739	RT	12.09	(11.31)	10.96
	ILS-12L-4	0.0729	350	7.05		6.39
Failure mode-S	ILS-12L-5	0.0743	350	7.62	(7.33)	6.91
	ILS-12L-6	0.0713	-65	7.67	(7.67)	6.95
$[90/\pm45]_{2S}$	ILS-12T-1	0.0729	RT	6.10		6.34
	ILS-12T-2	0.0715	RT	5.92		6.16
12 plies	ILS-12T-3	0.0738	RT	5.47	(5.83)	5.69
	ILS-12T-4	0.0740	350	4.00		4.16
Failure mode-S	ILS-12T-5	0.0754	350	4.60	(4.30)	4.78
	ILS-12T-6	0.0736	-65	5.07	(5.07)	5.27
$[\pm45]_{3S}$	ILS-12AL-1	0.0686	RT	5.97		5.97
	ILS-12AL-2	0.0709	RT	6.40		6.40
12 plies	ILS-12AL-3	0.0699	RT	6.40	(6.26)	6.40
	ILS-12AL-4	0.0736	350	4.05		4.05
Failure Mode-S, T	ILS-12AL-5	0.0702	350	3.97	(4.01)	3.97
	ILS-12AL-6	0.0712	-65	4.62	(4.62)	4.62

NOTE S = interlaminar shear; T = tensile flexure failure
Nominal width = 0.25 in.

$$\text{*Adjusted } F^{isu} = \sum_{i=1}^{N/2} A_i E_i \bar{y}_i \Bigg/ \left(2 \sum_{i=1}^{N/2} A_i E_i \bar{y}_i^{\,2} \right)$$

where summation is over one half the thickness and N = total number of plies.

TABLE XXX. CROSSPLIED GRAPHITE/EPOXY INTERLAMINAR SHEAR DATA (TYPE AS/3002 BATCH) (CONCLUDED)

Test Orientation	Specimen No.	Thickness (in.)	Temp (°F)	Stress F^{isu} (Ksi)	Stress Avg (Ksi)	Adjusted F^{isu*} (Ksi)
$[90_2/\pm45]_{2S}$	ILS-16T-1	0.0937	RT	6.68		6.86
	ILS-16T-2	0.0949	RT	6.56		6.73
16 plies	ILS-16T-3	0.0945	RT	6.49	(6.58)	6.66
	ILS-16T-4	0.0940	350	5.63		5.78
Failure mode-S	ILS-16T-5	0.0953	350	5.36	(5.49)	5.50
	ILS-16T-6	0.0957	-65	6.40	(6.40)	6.57
$[0_2/\pm45]_{2S}$	ILS-16L-1	0.0945	RT	11.12		10.30
	ILS-16L-2	0.0945	RT	12.79		11.85
16 plies	ILS-16L-3	0.0944	RT	12.02	(11.99)	11.14
	ILS-16L-4	0.0946	350	8.58		7.95
Failure mode-S	ILS-16L-5	0.0930	350	7.94	(8.26)	7.36
	ILS-16L-6	0.0930	-65	7.23	(7.23)	6.70
$[(0/\pm45/90]_{2S}$	ILS-16CL-1	0.0930	RT	8.72		7.80
	ILS-16CL-2	0.0940	RT	8.94		7.99
16 plies	ILS-16CL-3	0.0949	RT	8.98	(8.88)	8.02
	ILS-16CL-4	0.0948	350	7.58		6.77
Failure mode-S	ILS-16CL-5	0.0937	350	6.88	(7.23)	6.15
	ILS-16CL-6	0.0934	-65	11.84	(11.84)	10.58

NOTE S = interlaminar shear; T = tensile flexure failure
Nominal width = 0.25 in.

$$\text{*Adjusted } F^{isu} = \sum_{i=1}^{N/2} A_i E_i \bar{y}_i \Bigg/ \left(2 \sum_{i=1}^{N/2} A_i E_i \bar{y}_i{}^2 \right)$$

where summation is over one half the thickness and N = total number of plies.

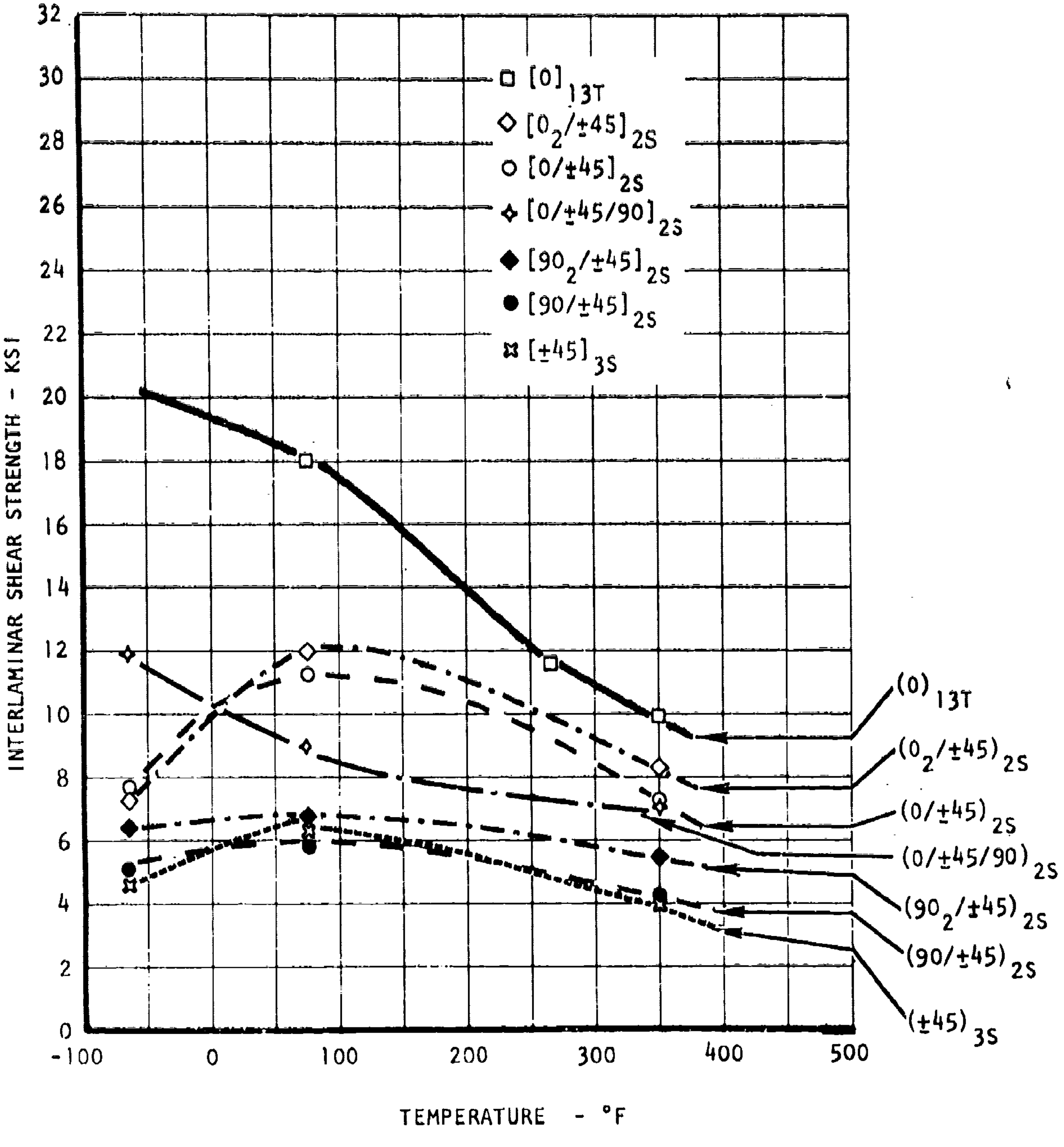


Figure 89. Interlaminar Shear Strength versus Temperature For Various Orientations - Type AS/3002 - Batch, Graphite/Epoxy

Tension Fatigue

The constant amplitude tension fatigue data (tables XXXI and XXXII) are plotted as maximum cyclic gross stress versus cycles to failure in figures 93, 94, 95, and 96, for unidirectional $[0]_{6T}$, and crossplied $[0/\pm45/90]_S$, $[0/\pm45]_S$, and $[90/\pm45]_S$, respectively. Data for $K_t = 1$ and $K_t = 3$ are shown, where $K_t = 1$ designates a plain or unnotched coupon and $K_t = 3$ designates a specimen with a center hole (0.1935 inch diameter) and not necessarily the actual values of the stress concentration factor. Examination of the plotted data shows the following conclusions for both unidirectional and crossplied orientations:

1. The S-N curves are relatively flat as expected for advanced composite materials.

2. The $K_t = 3$ data show flatter curve slopes than their comparable $K_t = 1$ data.

3. Stress levels generally below 60 percent of static ultimate should show no further degradation in fatigue life for $K_t = 1$ specimens.

4. Stress levels below 80 percent of static ultimate (open hole) should show no further degradation in fatigue life for $K_t = 3$ specimens.

The only exception to this is the $[90/\pm45]$ orientation, where the threshold stress is approximately 55 percent of static ultimate for $K_t = 1$ and 3 data.

Typical failed specimen photographs are shown in figures 90, 91, and 92 for unidirectional and crossplied laminates. It should be noted that fatigue failure was a tensile fracture at the minimum section (hole) for the $K_t = 3$ as expected for the crossplied laminates $[0/\pm45]_S$, $[90/\pm45]_S$, and $[0/\pm45/90]_S$. The unidirectional specimens, however, indicate longitudinal splitting and consequent transverse fracture away from the holes (figure 92). This is not an unusual failure, but represents the behavior of the unidirectional laminate layup.

TABLE XXXI. GRAPHITE/EPOXY TENSION FATIGUE DATA (TYPE AS/3002 BATCH) ROOM TEMPERATURE - $[0]_{6T}$, $[0/\pm45/90]_S$

Test Orientation	Specimen No.	Thickness (In.)	Width (In.)	K_t*	Maximum Stress (Ksi) Gross	Net	N-Cycles at Failure	Failure Location and/or Mode
$[0]_{6T}$	TF-UL1	0.0375	0.867	1	104.3	-	12,000	Test area**
	TF-UL2	0.0372	0.875	1	76.69		12,856,000	No failure**
	TF-UL3	0.0354	0.892	1	94.94		1,000	Test area**
	TF-UL4	0.0377	0.865	1	85.89		20,812,000	No failure**
	TF-UL5	0.0363	0.875	1	100.63		5,139,000	No failure
	TF-UL6	0.0384	0.875	3	59.52	76.42	1,066,000	Longitudinal splitting**
	TF-UL7	0.0382	0.875	3	75.47	96.92	15,000	Longitudinal splitting**
	TF-UL8	0.0345	0.865	3	73.89	95.17	1,000	Combined**
	TF-UL9	0.0379	0.865	3	72.00	92.73	****	Longitudinal and transverse failure**
	TF-UL10	0.0379	0.875	3	75.24	96.59	Static	Test area
$[0/\pm45/90]_S$	TF-8L1	0.0490	0.865	1	34.44		1,025,000	Test area**
	TF-8L2	0.0479	0.873	1	43.64		12,000	Test area**
	TF-8L3	0.0493	0.875	1	38.02		15,000	Test area**
	TF-8L4	0.0485	0.875	1	36.62		17,000	Test area**
	TF-8L5	0.0490	0.875	1	45.06		1,000	Test area**
	TF-8L6	0.0485	0.875	3	34.64	44.48	****	Test area***
	TF-8L7	0.0467	0.875	3	30.59	39.27	3,829,000	Test area***
	TF-8L8	0.0490	0.865	3	31.71	40.85	****	Test area***
	TF-8L9	0.0497	0.870	3	30.07	38.67	1,600,000	Test area***
	TF-8L10	0.0490	0.875	3	32.18	41.33	Static	Test area

NOTE
R = 0.05
*K_t = 1 is unnotched specimen
K_t = 3 is specimen with 0.1935 open hole in center
** = Amsler test machine, f = 93 cps
*** = Ivy-12 test machine, f = 20 cps
**** = Failed while loading

TABLE XXXII. GRAPHITE/EPOXY TENSION FATIGUE DATA (TYPE AS/3002 BATCH) ROOM TEMPERATURE - $[0/\pm45]_S$, $[90/\pm45]_S$

Orientation	Specimen No.	Thickness (In.)	Width (In.)	K_t*	Maximum Stress (Ksi) Gross	Net	N-Cycles at Failure	Failure Location and/or Mode
$[0/\pm45]_S$	TF-6L1	0.0386	0.870	1	41.67	-	5,285,000	No failure**
	TF-6L2	0.0390	0.875	1	51.32		2,000	Test area**
	TF-6L3	0.0350	0.867	1	51.98		62,000	Test area**
	TF-6L4	0.0389	0.868	1	44.38		5,989,000	Grip area**
	TF-6L5	0.0411	0.870	1	46.37		34,000	Test area**
	TF-6L6	0.0384	0.875	3	37.50	48.15	****	Test area**
	TF-6L7	0.0381	0.881	3	28.15	36.08	29,015,000	No failure**
	TF-6L8	0.0410	0.883	3	30.47	39.02	5,029,000	No failure***
	TF-6L9	0.0370	0.882	3	36.68	46.98	1,200	Test area***
	TF-6L10	0.0391	0.885	3	28.90	36.98	Static	---
$[90/\pm45]_S$	TF-6T1	0.0391	0.870	1	19.69	-	39,000	Test area**
	TF-6T2	0.0382	0.875	1	23.93	-	5,000	Test area**
	TF-6T3	0.0393	0.875	1	15.99	-	1,796,000	Test area**
	TF-6T4	0.0372	0.865	1	27.35	-	3,000	Test area**
	TF-6T5	0.0357	0.873	1	23.26	-	37,000	Test area**
	TF-6T6	0.0380	0.875	3	18.95	24.32	****	Test area***
	TF-6T7	0.0385	0.873	3	14.04	18.04	25,000	Test area***
	TF-6T8	0.0370	0.865	3	9.84	12.68	3,500,000	No failure***
	TF-6T9	0.0362	0.890	3	16.61	21.22	7,800	Test area***
	TF-6T10	0.0372	0.880	3	23.98	30.74	Static	Test area

NOTE: R = 0.05
*K_t = 1 is unnotched specimen
K_t = 3 is specimen with 0.1935 open hole in center
** Amsler test machine, f = 93 cps
*** Ivy 12 test machine, f = 20 cps
**** Failed while loading

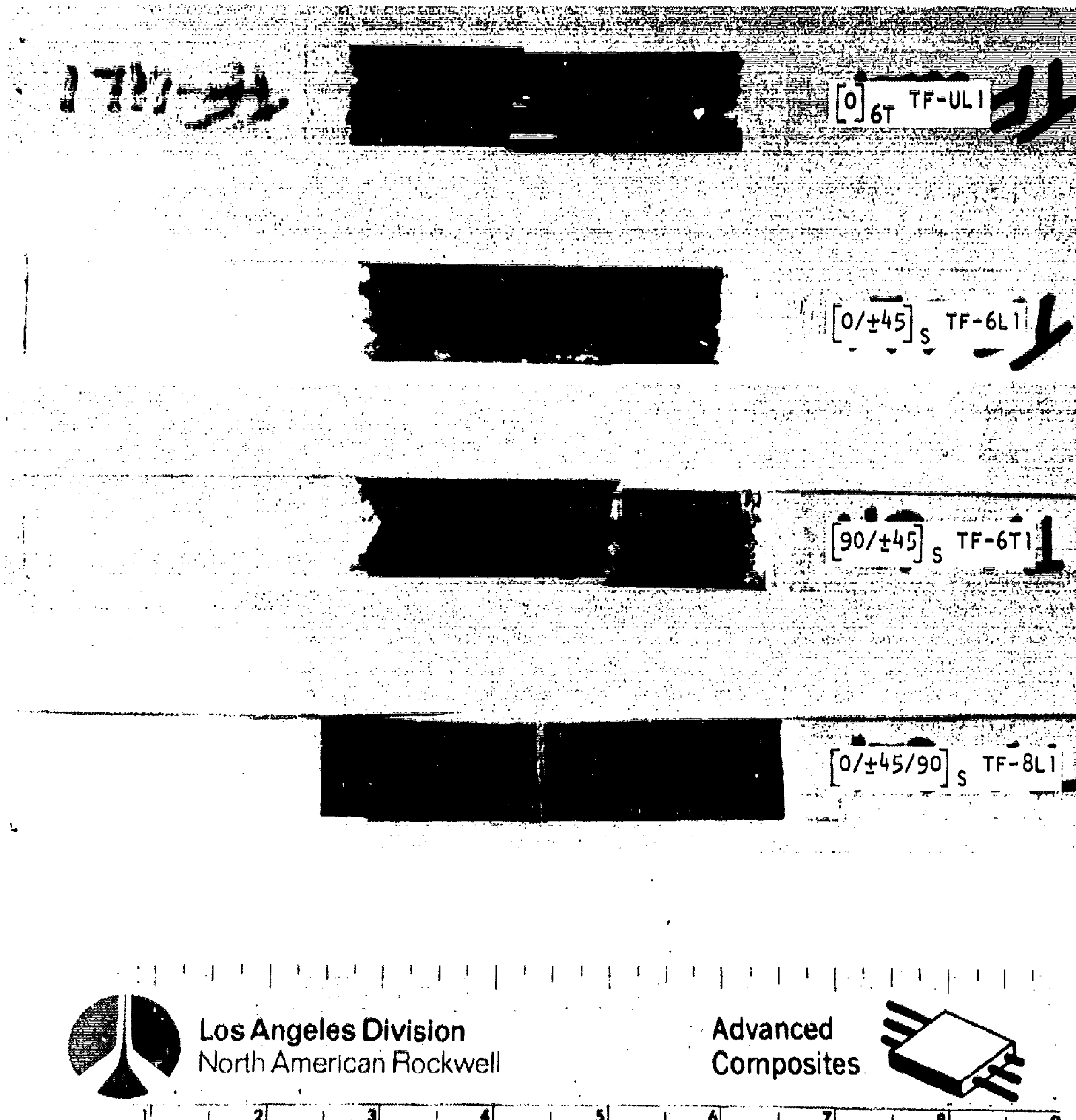


Figure 90. Typical Failed Tension Fatigue Graphite/Epoxy Specimens, $K_t = 1$, R = 0.05, RT, Type AS/3002 - Batch

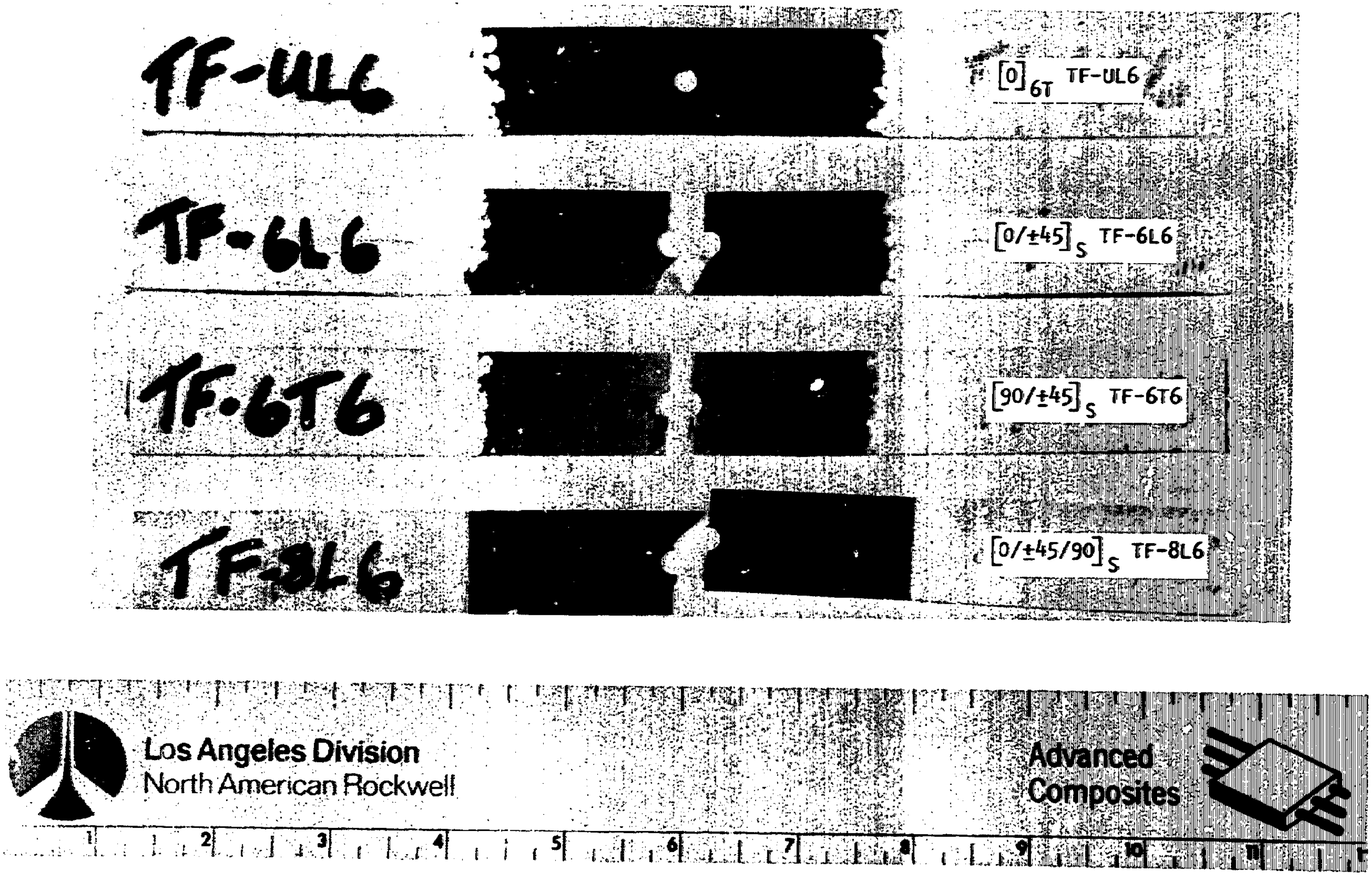


Figure 91. Typical Failed Tension Fatigue Graphite/Epoxy Specimens, $K_t = 3$, $R = 0.05$, Room Temperature, Type AS/3002 - Batch

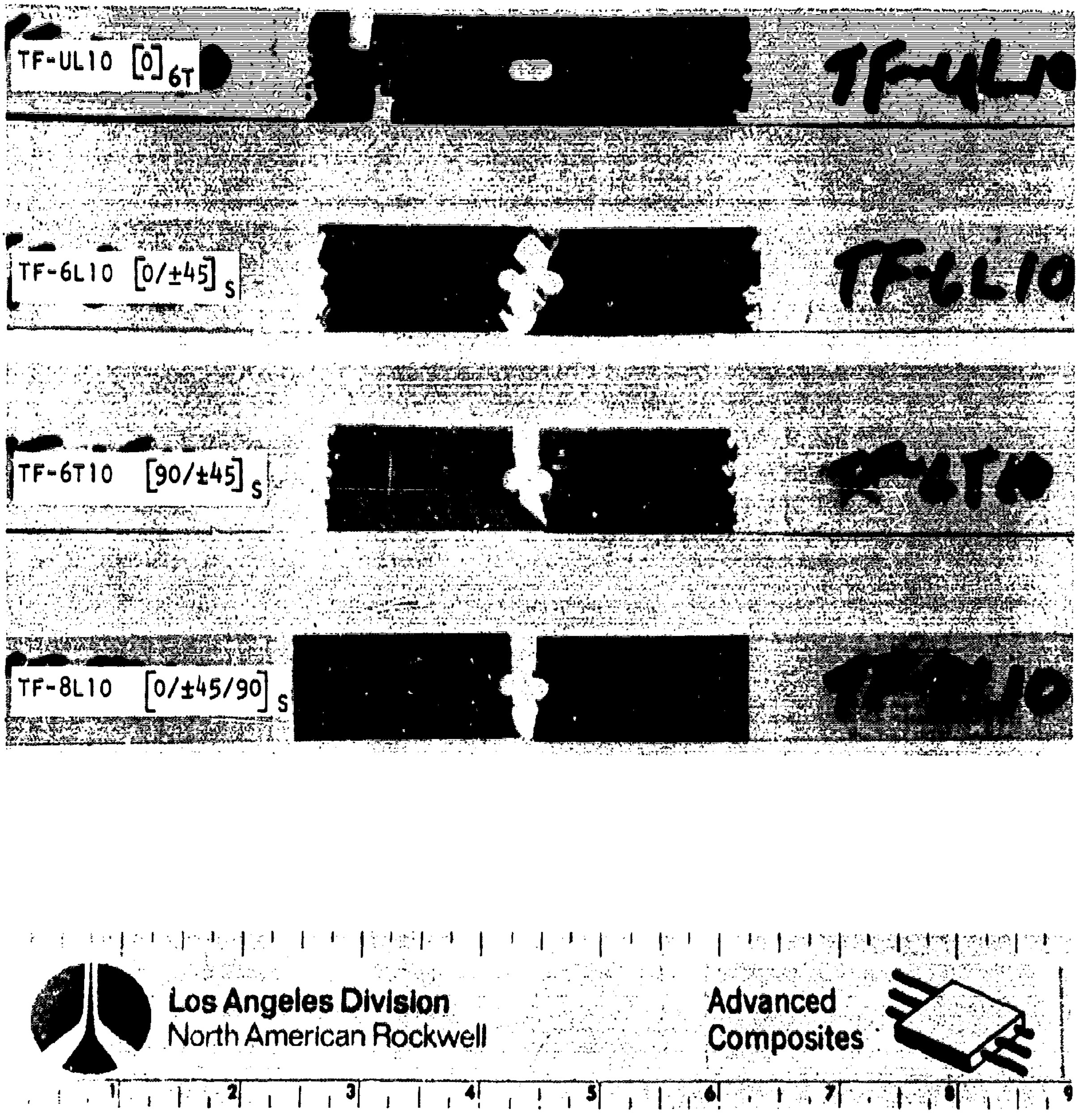


Figure 92. Typical Failed Tension Fatigue Graphite/Epoxy Specimens, $K_t = 3$, R = 0.05, 350° F, Type AS/3002 - Batch

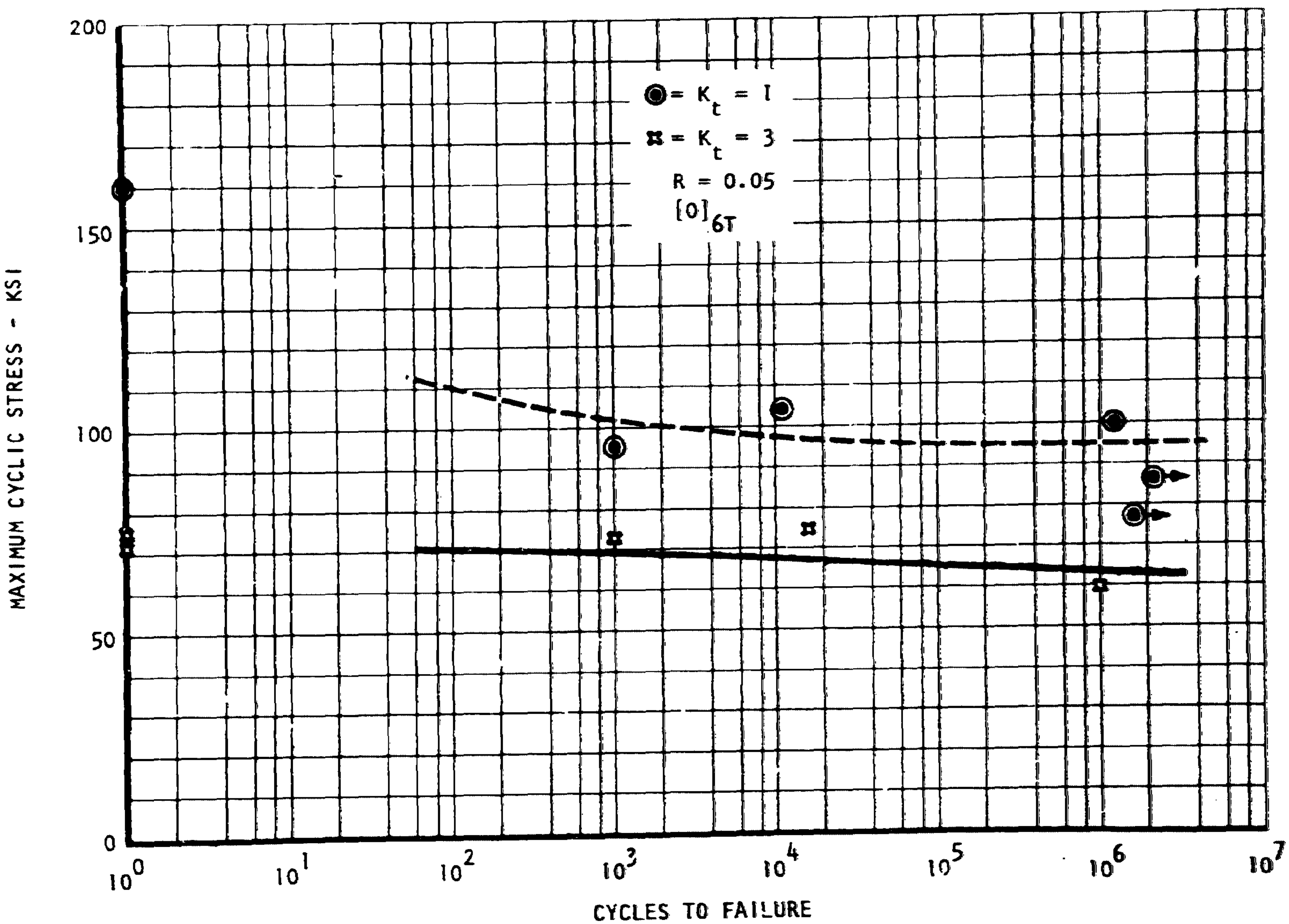


Figure 93. Constant Amplitude Tension Fatigue, Unidirectional Graphite/Epoxy Type AS/3002 - Batch, Room Temperature, R = 0.05

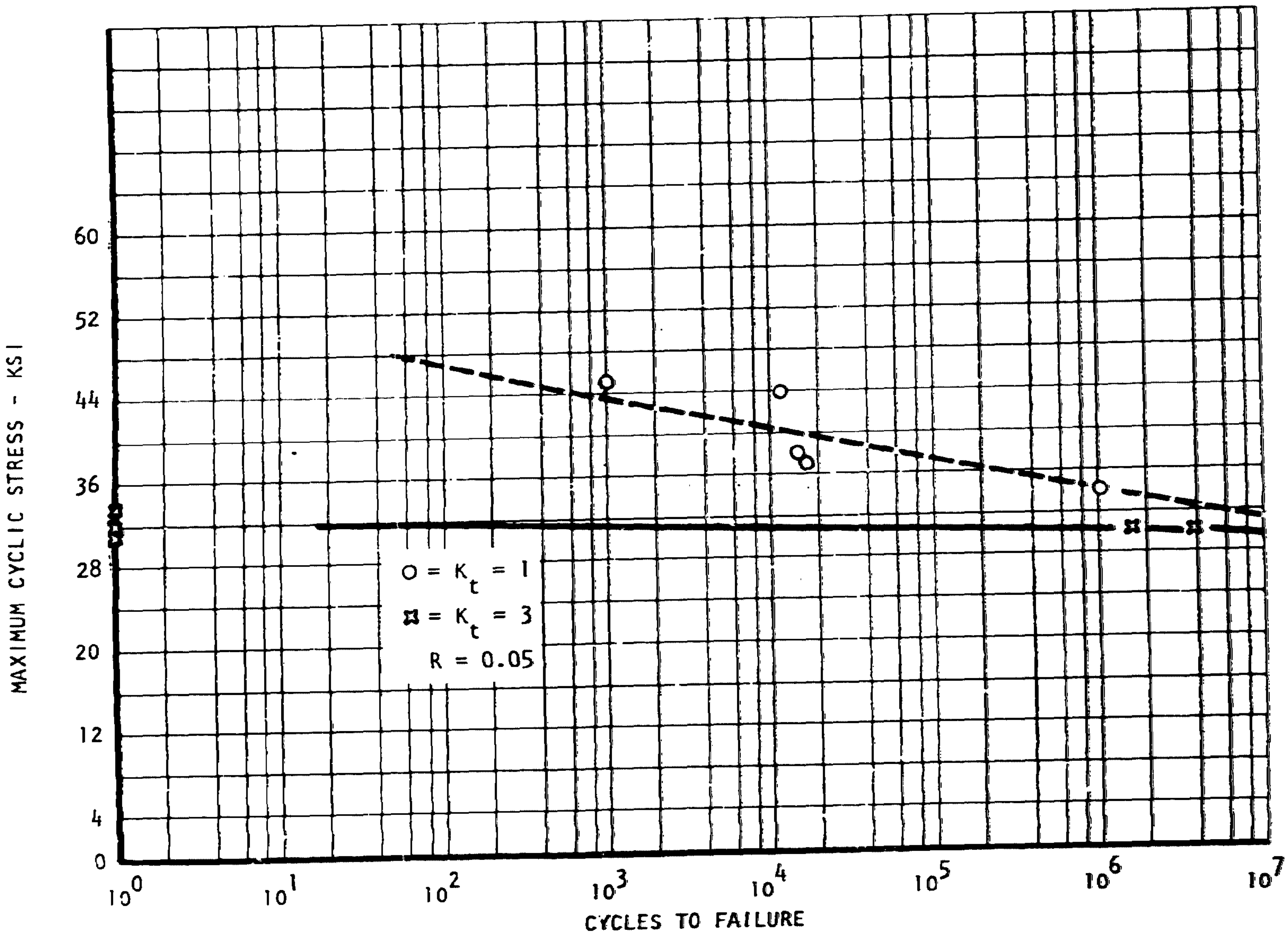


Figure 94. Constant Amplitude Tension Fatigue, $[0/\pm 45/90]_S$ Graphite/Epoxy Type AS/3002 - Batch, Room Temperature, R = 0.05

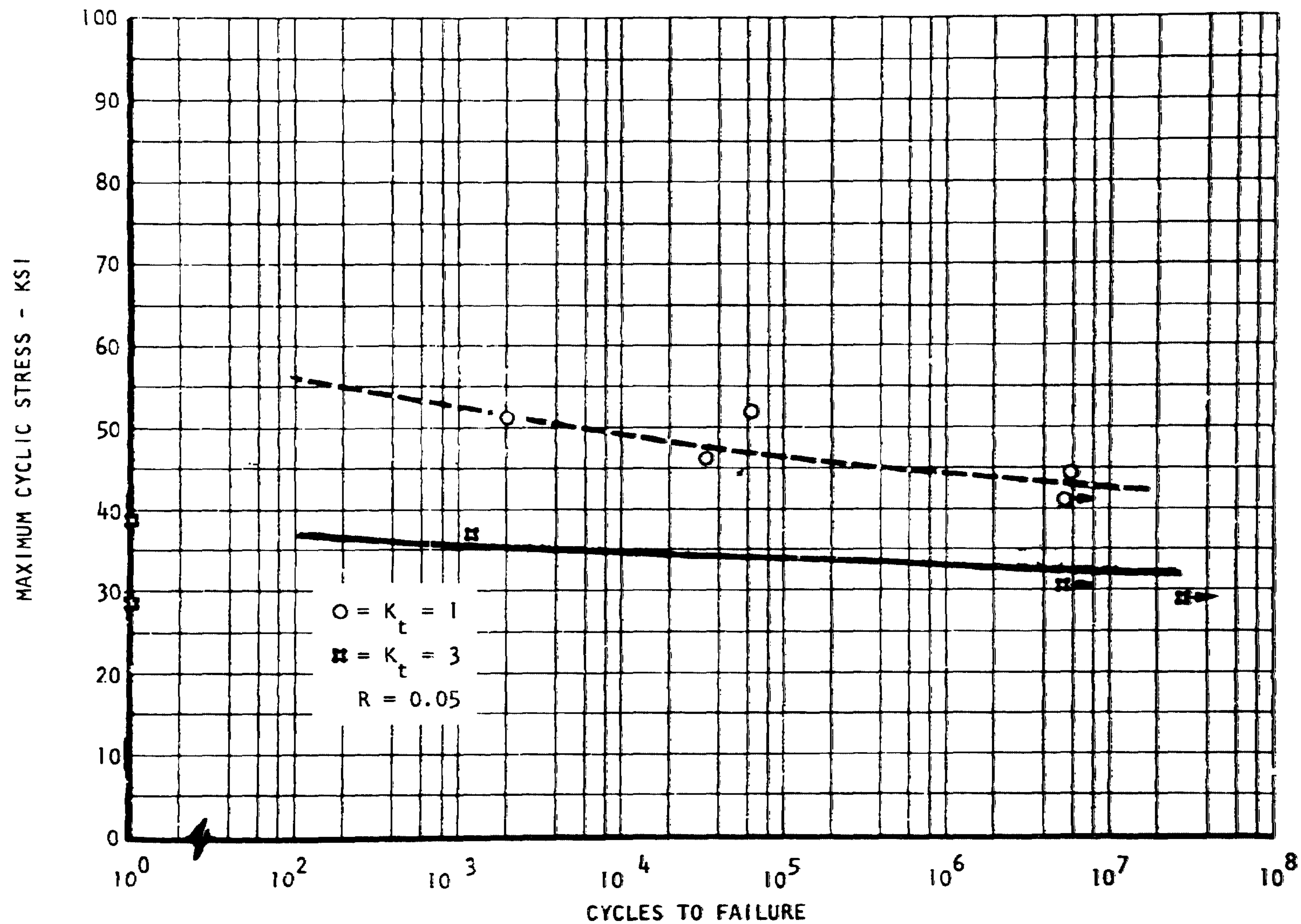


Figure 95. Constant Amplitude Tension Fatigue, $[0/\pm 45]_S$ Graphite/Epoxy Type AS/3002 - Batch, Room Temperature, R = 0.05

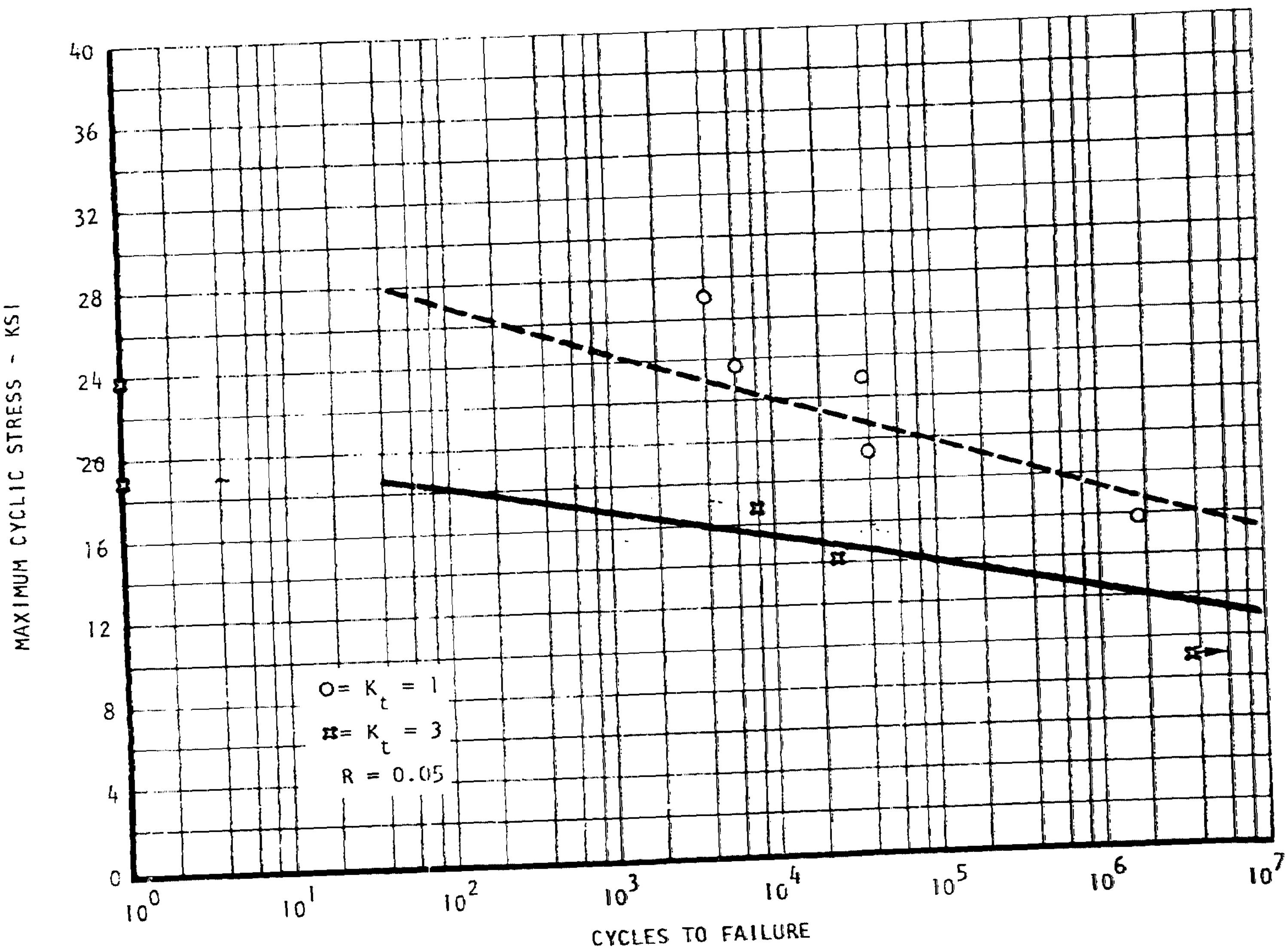


Figure 96. Constant Amplitude Tension Fatigue, $[90/\pm45]_S$ Graphite/Epoxy Type AS/3002 - Batch, Room Temperature, R = 0.05

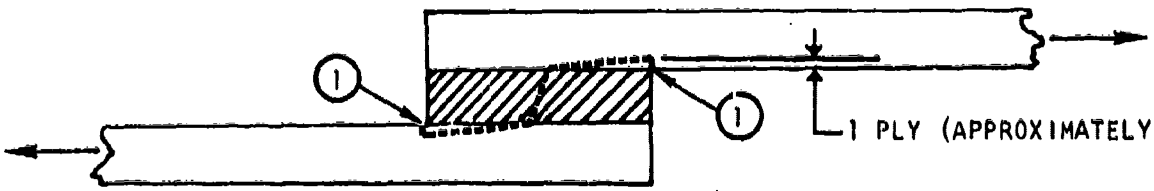
JOINTS

BONDED JOINTS

Tension-Loaded Single Lap Joints

Treated Graphite/Epoxy to Graphite/Epoxy (Type AS/3002)

Static tension data for bonded single lap joints with crossplied graphite/epoxy (Type AS/3002) adherends are presented in tables XXXIII and XXXIV. Two laminate orientations were tested ($[0/\pm45]_S$ and $[0_2/\pm45]_S$) with three lap lengths (nominal 0.5, 1.0, and 1.5 inches) and two test temperatures (room temperature and 350°F) being used for each laminate. Typical failed specimens are shown in figure 97. The mode of failure was one of interlaminar shear as shown in the following drawing (exaggerated to show detail).



From an examination of the specimens, it appears that the Metlbond 329-7 adhesive mixes with the epoxy in the first ply of each of the adherends. The mode of failure could be caused by a stress concentration at the corner of the bond (point 1 in drawing) which, when loaded, causes a peel between the first and second ply of the adherends as is shown by the dotted line. A typical failed specimen is shown in the following drawing (exaggerated to show detail).

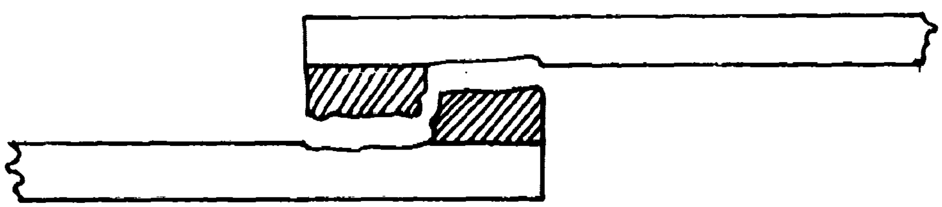


Figure 98 presents a plot of adhesive shear stress versus lap length to adherend thickness ratio. As expected, the adhesive shear stress ultimate decreases with increasing lap length to adherend thickness ratios. The major item of interest here, though, is that for this group of tests an increase in strength at 350°F (15 to 55 percent higher) over that at room temperature was evidenced. Beneficial stress redistribution due to the added ductility of the adhesive at 350°F probably contributed to the increased strengths. For design purposes the lower bound of the room temperature values would be appropriate. Comparison with untreated fiber data (see figure 101) shows a significant increase in lap joint strength.

TABLE XXXIII. BONDED SINGLE LAP JOINT TEST DATA, GRAPHITE-GRAPHITE $[0/\pm 45]_S$

Adherends: Type AS/3002 Graphite/Epoxy $[0/\pm 45]_S$
Adhesive: Metlbond 329-7

Specimen No.	Temp (°F)	Width (in.)	Lap Length (in.)	Bond Area (sq in.)	Load (lb)	Adhesive Stress (psi)	Avg Stress (psi)	Joint Efficiency Avg*
BGG-6LA-1	RT	0.996	0.5	0.498	1,205	2,420		
BGG-6LA-2	RT	0.993	0.5	0.497	1,005	2,020	(2,200)	(0.44)
BGG-6LA-3	RT	0.994	0.5	0.497	1,080	2,170		
BGG-6LA-4	350	1.005	0.5	0.503	930	1,850		
BGG-6LA-5	350	1.003	0.5	0.502	1,030	2,050	(1,960)	(0.48)
BGG-6LA-6	350	1.010	0.5	0.505	1,000	1,980		
BGG-6LB-1	RT	0.995	1.0	0.995	1,450	1,460		
BGG-6LB-2	RT	0.995	1.0	0.995	1,545	1,550	(1,480)	(0.59)
BGG-6LB-3	RT	0.993	1.0	0.993	1,425	1,440		
BGG-6LB-4	350	1.002	1.0	1.002	1,745	1,740		
BGG-6LB-5	350	0.997	1.0	0.997	1,640	1,650	(1,680)	(0.82)
BGG-6LB-6	350	1.001	1.0	1.001	1,645	1,640		
BGG-6LC-1	RT	0.998	1.5	1.497	1,285	860		
BGG-6LC-2	RT	0.998	1.5	1.497	1,630	1,090	(1,030)	(0.61)
BGG-6LC-3	RT	0.995	1.5	1.493	1,690	1,130		
BGG-6LC-4	350	0.997	1.5	1.496	1,830	1,220		
BGG-6LC-5	350	1.000	1.5	1.500	1,820	1,210	(1,180)	(0.86)
BGG-6LC-6	350	0.995	1.5	1.493	1,645	1,100		

NOTE 1. Nominal thickness = 0.036 in.
2. Failure mode = interlaminar shear in composite.

*Joint strength/basic laminate strength.

TABLE XXXIV. BONDED SINGLE LAP JOINT TEST DATA, GRAPHITE-GRAPHITE $[0_2/\pm45]_S$

Adherends: Type AS/3002 Graphite/Epoxy $[0_2/\pm45]_S$
Adhesive: Metlbond 329-7

Specimen No.	Temp (°F)	Width (in.)	Lap Length (in.)	Bond Area (sq in.)	Load (lb)	Adhesive Stress (psi)	Avg Stress (psi)	Joint Efficiency Avg*
BGG-8CLA-1	RT	0.995	0.5	0.498	605	1,220		
BGG-8CLA-2	RT	0.995	0.5	0.498	720	1,450	(1,350)	(0.15)
BGG-8CLA-3	RT	0.995	0.5	0.498	685	1,380		
BGG-8CLA-4	350	0.998	0.5	0.499	770	1,540		
BGG-8CLA-5	350	0.995	0.5	0.498	755	1,520	(1,620)	(0.21)
BGG-8CLA-6	350	0.995	0.5	0.498	895	1,800		
BGG-8CLB-1	RT	0.998	1.0	0.998	935	940		
BGG-8CLB-2	RT	0.997	1.0	0.997	930	930	(920)	(0.20)
BGG-8CLB-3	RT	0.995	1.0	0.995	875	880		
BGG-8CLB-4	350	0.995	1.0	0.995	1,385	1,390		
BGG-8CLB-5	350	0.997	1.0	0.997	1,235	1,240	(1,380)	(0.36)
BGG-8CLB-6	350	0.995	1.0	0.995	1,500	1,510		
BGG-8CLC-1	RT	0.996	1.5	1.494	1,265	850		
BGG-8CLC-2	RT	0.999	1.5	1.499	1,130	750	(840)	(0.28)
BGG-8CLC-3	RT	0.996	1.5	1.494	1,355	910		
BGG-8CLC-4	350	0.995	1.5	1.493	1,290	860		
BGG-8CLC-5	350	0.995	1.5	1.493	1,570	1,050	(1.020)	(0.40)
BGG-8CLC-6	350	0.995	1.5	1.493	1,720	1,150		

NOTE 1. Nominal thickness = 0.048 in.
2. Failure mode = interlaminar shear in composite
*Joint strength/basic laminate strength

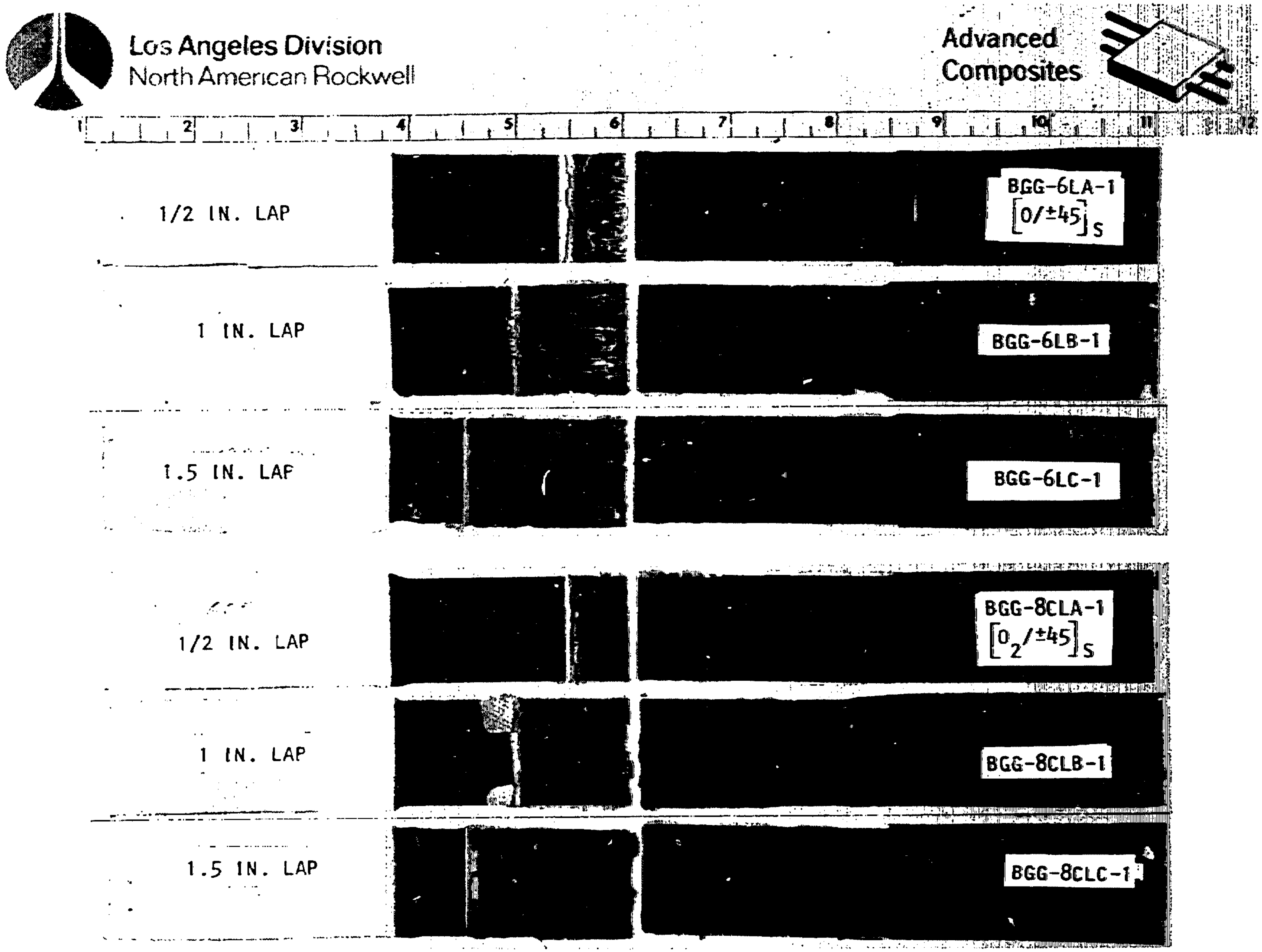


Figure 97. Typical Failed Bonded Single-Lap Joint Specimens - Metlbond 329-7 Adhesive, Graphite to Graphite Adherends, Type AS/3002 - Batch, Room Temperature

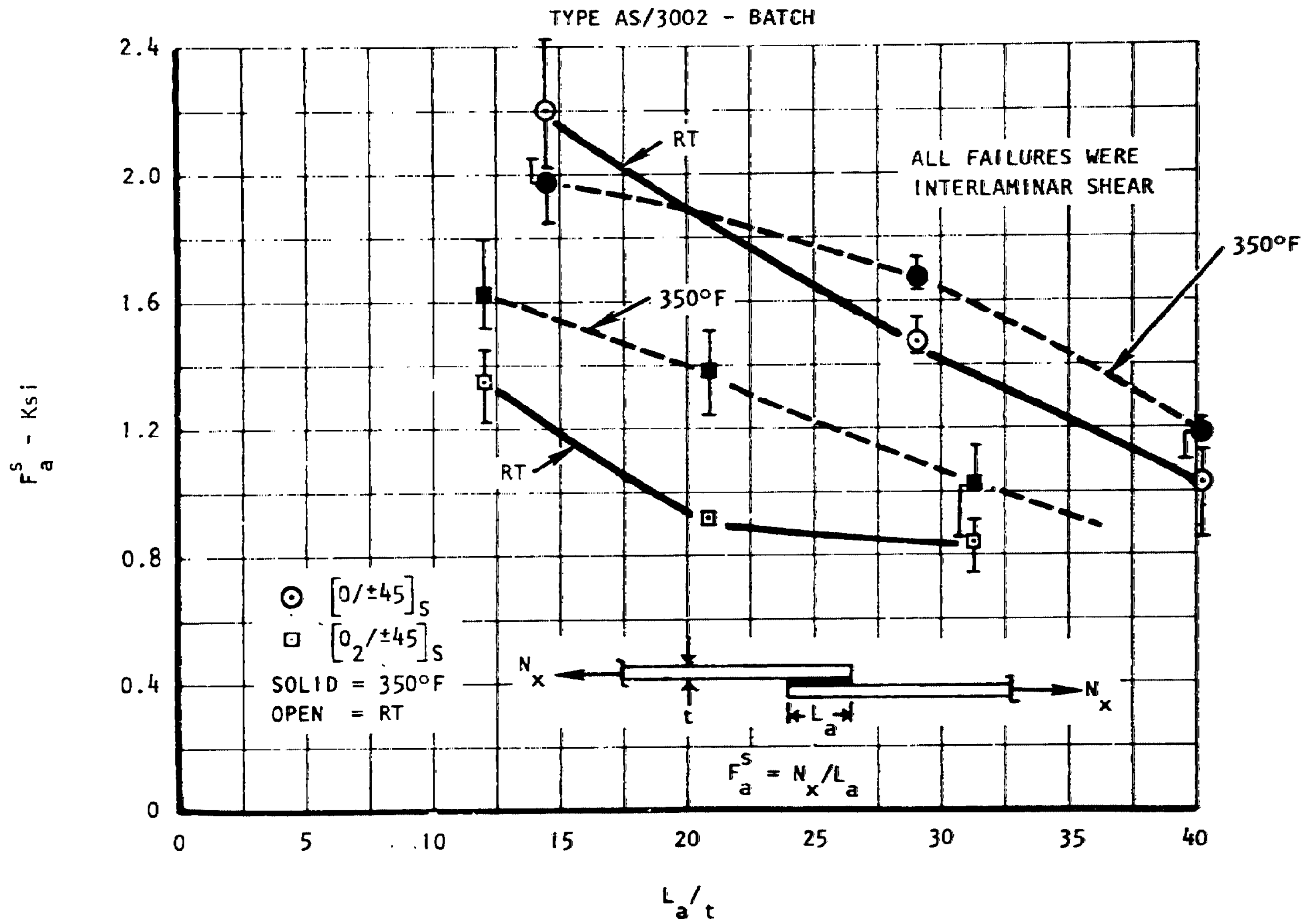


Figure 98. Graphite/Epoxy to Graphite/Epoxy Single-Overlap Bonded Joint Strength - Metlbond 329-7 Adhesive - Room Temperature and 350°F

From figure 98 it appears that the bonded lap joints with $[0/\pm45]_S$ graphite/epoxy adherends attained higher joint strengths than those with $[0_2/\pm45]_S$ graphite/epoxy adherends. Futhermore, a comparison of joint efficiencies, where the joint efficiency is defined as joint strength divided by basic adherend laminate strength, shows that the higher the percentage of ±45° plies the higher the joint efficiency. Also, for adherends with the same percentage of ±45° plies, the joint efficiency is highest where the percentage of 0° plies is lowest. This is primarily due to the fact that the basic laminate strength itself varies inversely with increasing percentage of ±45° plies.

Untreated Graphite/Epoxy to Graphite/Epoxy (Type A/3002)

Table XXXV presents static tension test data for bonded single lap joint specimens with $[0/\pm45/90]_S$ graphite/epoxy Type A/3002 batch adherends. The adhesive used was Metlbond 329-7. Three lap lengths were tested at both room temperature and 350°F, and typical failed specimens are shown in figures 99 and 100. All room-temperature failures were interlaminar shear, whereas the 350°F specimens had cohesive or combined cohesive and interlaminar shear failures.

Figure 101 shows the Metlbond 329-7 adhesive bonded single lap joint data for graphite/epoxy to graphite/epoxy adherends.. Both room-temperature and 350°F data are shown. Trend curves drawn through the average of three test values versus the parameter L_a/t show the expected strength reduction as L_a/t increases. Interlaminar shear failures in the composite at room temperature and cohesive failures of the bond at 350°F indicate a transitional failure mode behavior. The room-temperature adhesive strengths were all higher than the 350°F values (20 percent on the average). This is a reversal of the trend observed for the treated (Type AS/3002) bonded single lap joints presented previously. Note the joint efficiency values varies from 0.21 (0.5 in lap) to 0.34 (1.5 in lap) at room temperature. The average joint efficiency at 350°F for the 1.5-inch lap was 0.41 based on a basic laminate strength of 2,592 lb/in.

Joint Efficiency Summary - Graphite to Graphite

Table XXXVI presents room-temperature and 350°F bonded single lap joint efficiencies for both treated (Type AS/3002) and untreated (Type A/3002) graphite/epoxy joints. It will be noted that the higher the percentage of ±45° plies, the lower the basic allowable laminate strength and, hence, the closer the basic allowable strength is to the maximum allowable adhesive strength.

TABLE XXXV. GRAPHITE-GRAPHITE STATIC SINGLE LAP JOINT TEST RESULT, A/3002 (BATCH), $[0/\pm45/90]_S$

Adherends: Graphite/Epoxy to Graphite/Epoxy $[0/\pm45/90]_S$
Adhesive: Metlbond 329-7

Specimen No.	Temp (°F)	Width (in.)	Composite Thick. (in.)	Adhesive Thick. (in.)	Lap Length (in.)	Bond Area (sq in.)	Load (lb.)	Adhesive Stress (psi)	Failure Mode (%) *
BGG-8LA1	RT	0.994	0.051	0.008	0.50	0.497	665	1,338	S
BGG-8LA2	RT	0.952	0.052	0.008	0.53	0.505	625	1,239	S
BGG-8LA3	RT	0.997	- -	---	0.50	0.498	660	1,325	S
BGG-8LA4	350	1.000	0.048	0.009	0.52	0.520	457	879	C
BGG-8LA5	350	0.960	0.050	0.010	0.53	0.509	400	786	C
BGG-8LA6	350	0.996	0.051	0.009	0.52	0.518	536	1,035	C
BGG-8LB1	RT	0.990	0.050	0.010	1.00	0.990	863	872	S
BGG-8LB2	RT	0.996	0.051	0.010	1.00	0.996	855	859	S
BGG-8LB3	RT	0.991	0.050	0.009	1.00	0.991	935	943	S
BGG-8LB4	350	0.985	0.052	0.010	1.00	0.985	750	761	C
BGG-8LB5	350	1.000	0.049	0.009	1.00	1.000	755	755	C
BGG-8LB6	350	0.995	0.049	0.009	1.00	0.995	755	759	C
BGG-8LC1	RT	1.000	0.050	0.011	1.50	1.500	1,080	720	S
BGG-8LC2	RT	1.004	0.050	0.010	1.50	1.506	995	660	[illegible]
BGG-8LC3	RT	1.000	0.051	0.010	1.50	1.500	1,140	760	S
BGG-8LC4	[illegible]	0.967	0.050	0.011	1.52	1.470	1,050	714	C
BGG-8LC5	350	0.991	0.051	0.010	1.53	1.516	1,005	663	C
BGG-8LC6	350	0.975	0.050	0.009	1.50	1.462	1,075	735	C60, S40

*Failure mode code: S = interlaminar shear in composite; C = cohesive

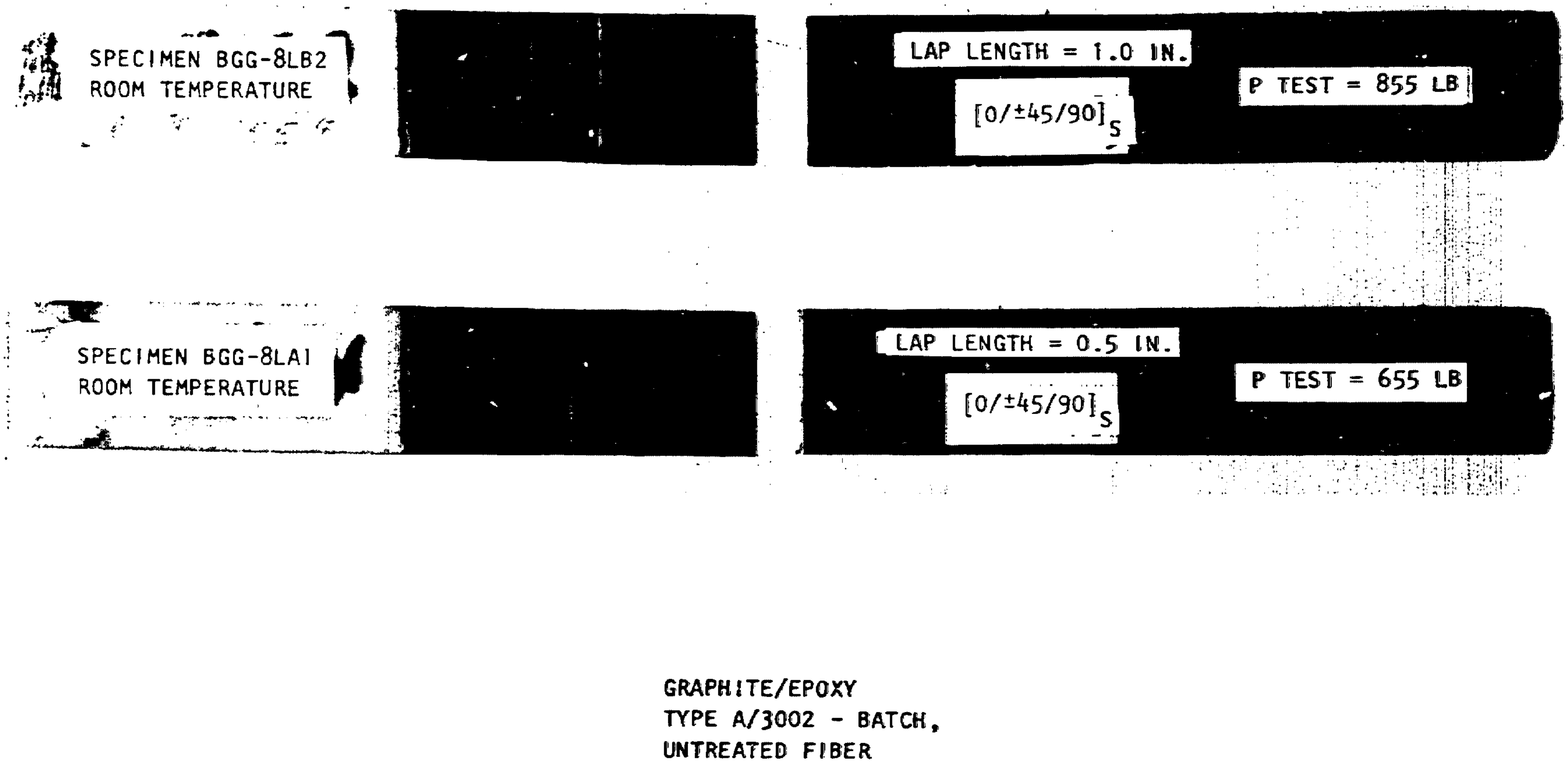
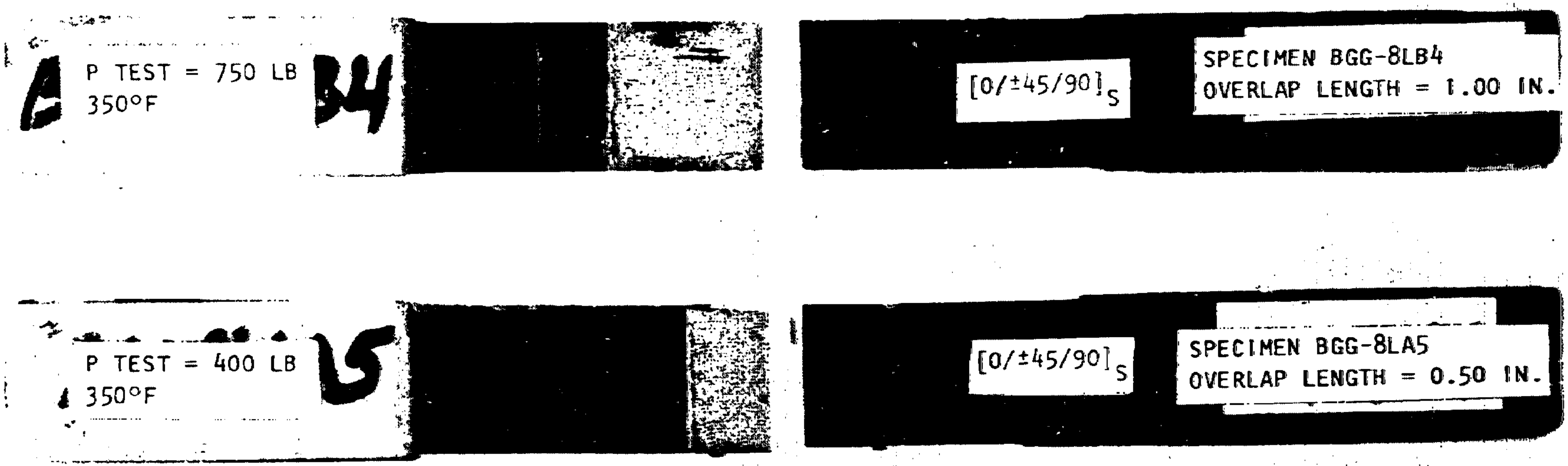


Figure 99. Typical Failed Single-Lap Bonded Joint Specimens - Metlbond 329-7 Adhesive - Graphite/Epoxy to Graphite/Epoxy - Room Temperature



GRAPHITE/EPOXY
TYPE A/3002 - BATCH,
UNTREATED FIBER

Figure 100. Typical Failed Single-Lap Bonded Joint Specimens - Metlbond 329-7 Adhesive - Graphite/Epoxy to Graphite/Epoxy, 350°F

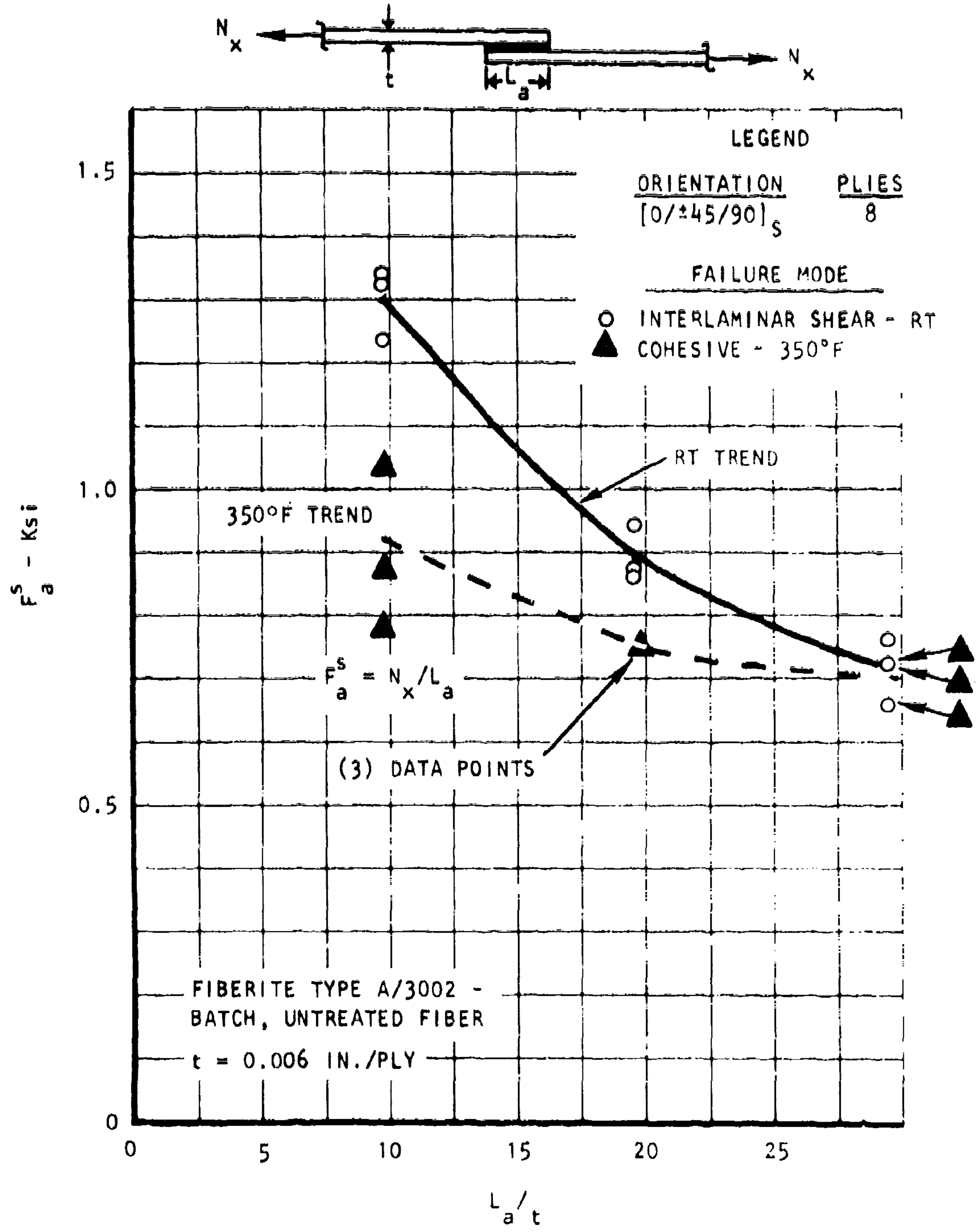


Figure 101. Graphite/Epoxy to Graphite/Epoxy Single-Overlap Bonded Joint Strength Metlbond 329-7 Adhesive - Room Temperature and 350°F

TABLE XXXVI. SINGLE LAP BONDED JOINT EFFICIENCY SUMMARY

Adherends: Graphite to Graphite

Laminate Orientation	Lap Length Nominal (in.)	N_X Joint (lb/in.)	N_X Basic Laminate (lb/in.)	Joint Efficiency**
$\left[0/\pm 45\right]_S^*$				
RT	1.50	1,545	2,520	0.61
350°F	1.50	1,770	2,052	0.86
$\left[0_2/\ 45\right]_S^*$				
RT	1.50	1,260	4,512	0.28
350°F	1.50	1,530	3,840	0.40
$\left[0/\pm 45/90\right]_S$				
RT	1.50	1,070	3,120	0.34
350°F	1.50	1,056	2,592	0.41

*Treated Type AS/3002 Batch adherends; all others [illegible] untreated Type A/3002 batch adherends

**Average joint efficiency = joint strength/basic laminate strength from predicted values (section V)

Untreated Graphite/Epoxy to Steel

Static test data for graphite/epoxy to steel single lap joints bonded with Metlbond 329-7 adhesive are presented in table XXXVII. One graphite/epoxy (Type A/3002, batch untreated) laminate orientation $[0/\pm45/90]_S$ was tested. Three lap lengths (nominal 0.5, 1.0, and 1.5 inches were tested at both room and elevated temperatures, and typical failed room-temperature and 350°F test specimens are shown in figures 102 and 103, respectively. The basic room-temperature failure mode was laminate interlaminar shear for 0.50- and 1.0-inch lap lengths, while the failure was a cohesive type for 1.5-inch laps. All 350°F failures were a combination of laminate interlaminar shear and adhesive failures, (table XXXVII).

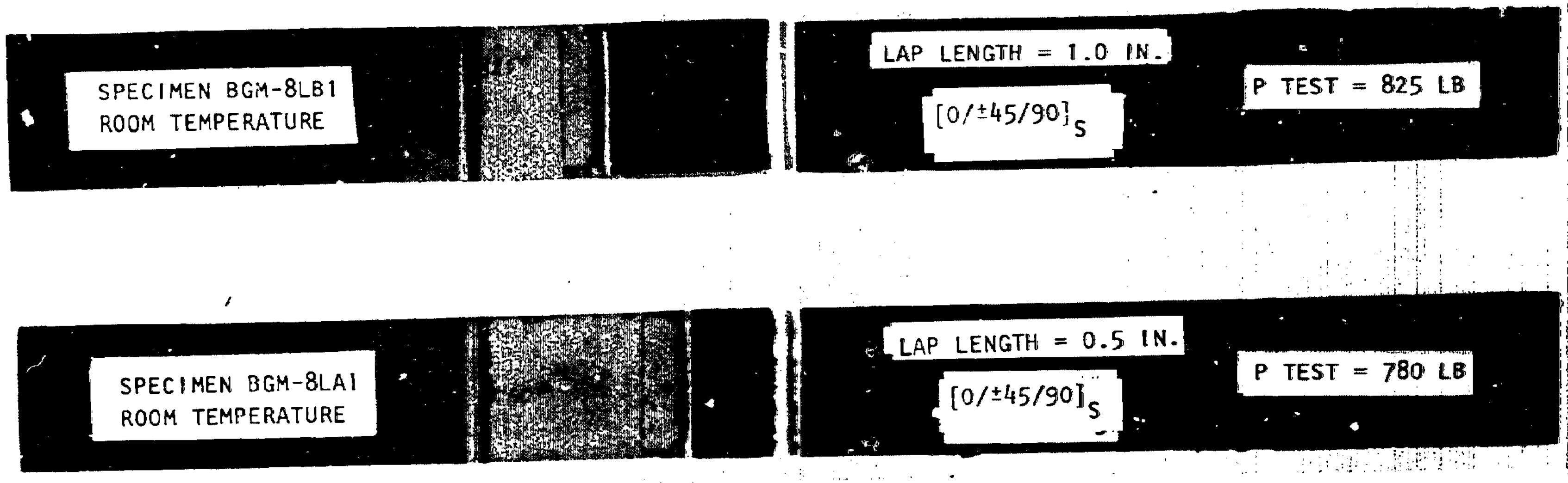
The adhesive shear strengths were comparable to those from graphite/epoxy to graphite/epoxy (Type A/3002, batch untreated) bonded single lap joints presented in table XXXV, although the failure modes for the 350°F tests were different. Figure 104 shows a plot of adhesive shear strength versus lap length to adherend thickness ratio. The trend is the reverse of that for the graphite-graphite joints, with the 350°F curve for the most part being above the room-temperature curve. This could possibly be due to a better distribution of adhesive stresses caused by the Metlbond 329-7 becoming more ductile at 350°F. In any case, the composite-to-composite and the composite-to-steel joints yielded comparable strengths. The average joint efficiencies attained for the 1.5-inch lap length specimens were 0.30 and 0.41 at room temperature and 350°F, respectively.

TABLE XXXVII. GRAPHITE-STEEL STATIC SINGLE LAP JOINT TEST RESULTS

Adherends: Graphite/Epoxy $[0/\pm 45/90]_S^{**}$ to Steel (HP-9-4-20)
Adhesive: Metlbond 329-7

Specimen No.	Temp (°F)	Width (in.)	Composite Thick. (in.)	Adhesive Thick. (in.)	Lap Length (in.)	Bond Area (sq in.)	Load (lb.)	Adhesive Stress (psi)	Failure Mode (%) *
BGM-8LA1	RT	1.005	0.052	0.006	0.50	0.503	780	1,551	S
BGM-8LA2	RT	1.003	0.051	0.005	0.54	0.542	760	1,402	S
BGM-8LA3	RT	0.998	0.051	0.004	0.50	0.499	765	1,533	S
BGM-8LA4	350	0.997	0.051	0.004	0.54	0.534	745	1,395	S40, A60
BGM-8LA5	350	1.001	0.051	0.005	0.53	0.530	550	1,038	S20, A80
BGM-8LA6	350	1.002	0.050	0.005	0.52	0.521	775	1,487	S34, A66
BGM-8LB1	RT	1.001	0.052	0.007	1.00	1.001	825	824	S
BGM-8LB2	RT	0.996	0.051	0.008	1.04	1.036	790	763	S
BGM-8LB3	RT	1.009	---	---	1.00	1.009	778	771	S
BGM-8LB4	350	1.000	0.051	0.005	1.00	1.000	952	952	S25, A75
BGM-8LB5	350	0.995	0.053	0.006	1.00	0.995	955	960	S45, A55
BGM-8LB6	350	1.000	0.053	0.006	1.05	1.050	910	867	S35, A65
BGM-8LC1	RT	1.000	0.050	0.004	1.50	1.500	985	657	S
BGM-8LC2	RT	0.997	0.053	0.007	1.50	1.495	870	582	S
BGM-8LC3	RT	1.003	0.052	0.009	1.50	1.504	945	628	S
BGM-8LC4	350	1.000	0.052	0.007	1.48	1.480	1,002	677	S20, A80
BGM-8LC5	350	0.990	0.050	0.006	1.50	1.485	1,120	754	S40, A60
BGM-8LC6	350	1.000	---	0.006	1.48	1.480	1,105	747	S75, A25

*Failure mode code: S = interlaminar shear in composite; C = cohesive; A = adhesive
**Untreated - batch Type A/3002



GRAPHITE/EPOXY
TYPE A/3002 - BATCH,
UNTREATED FIBER

Figure 102. Typical Failed Single-Lap Bonded Joint Specimens - Metlbond 329-7 Adhesive - Graphite/ Epoxy to Steel - Room Temperature

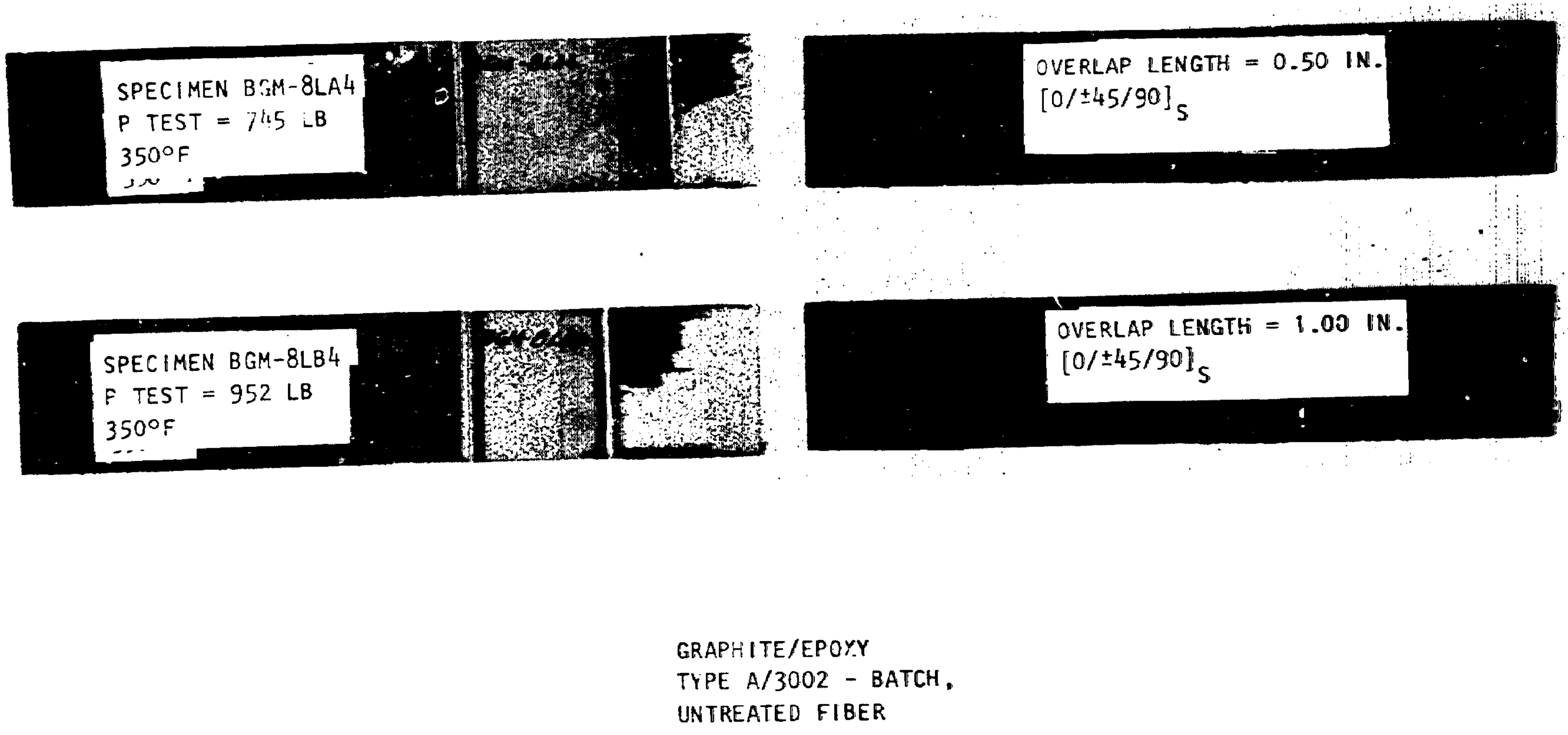


Figure 103. Typical Failed Single-Lap Bonded Joint Specimens - Metlbond 329-7 Adhesive - Graphite/Epoxy to Steel. 350°F

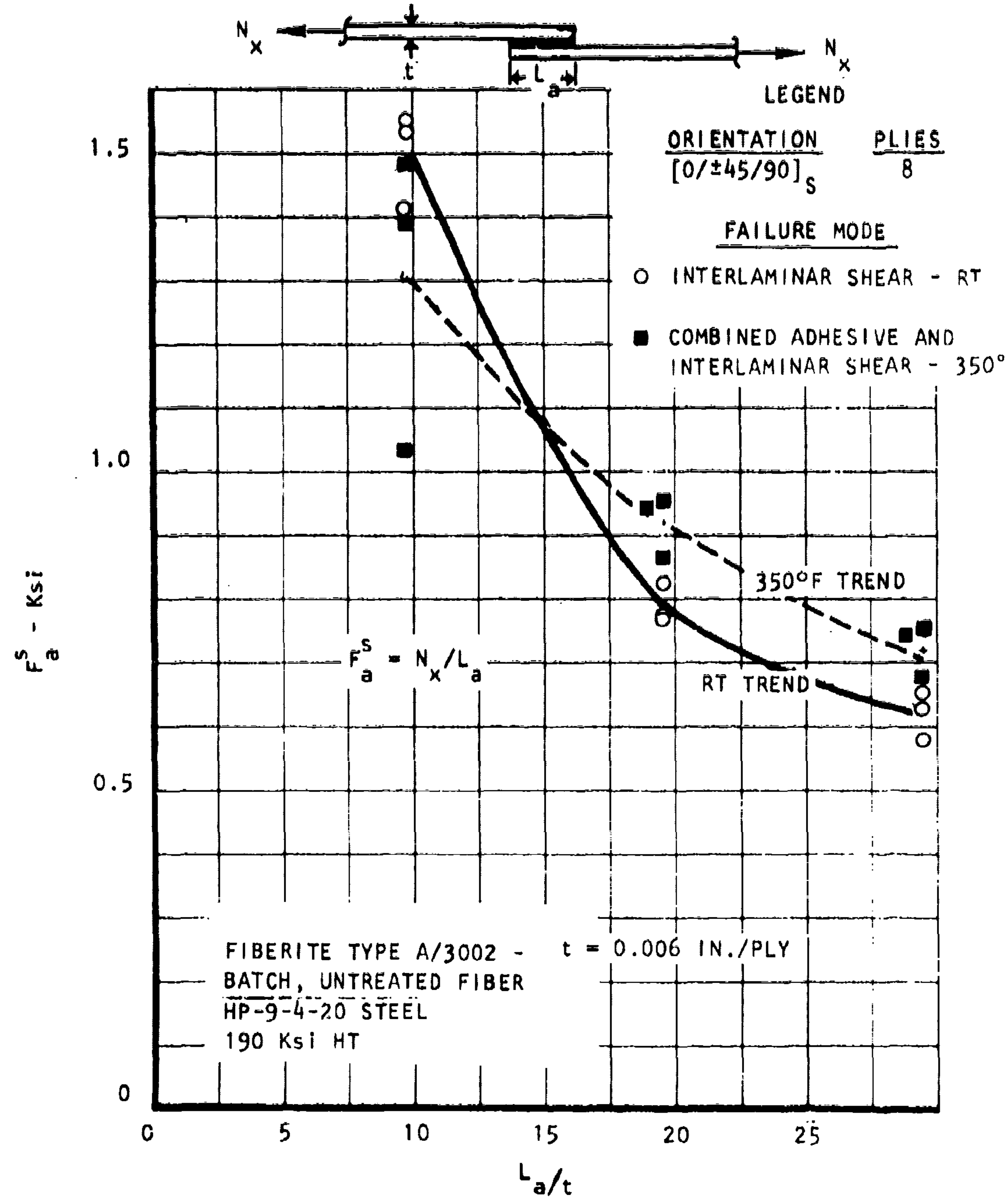


Figure 104. Graphite/Epoxy to Steel Single-Overlap Bonded Joint Strength - Metlbond 329-7 Adhesive - Room Temperature and 350°F

Tension-Loaded Symmetrical Scarf Joints

Treated Graphite/Epoxy to Titanium

Tables XXXVIII through XL present static tension data for various crossplied graphite/epoxy to titanium (6Al-4V) bonded symmetrical scarf joint specimens. Three different graphite/epoxy laminate orientations ($[0/\pm45]_{2S}$, $[0/\pm45/90]_{2S}$, and $[0_2/\pm45]_{2S}$) and two test temperatures were used, these being room temperature and 350°F. Also, three different lap lengths were tested for each orientation: 0.4, 0.7, and 1.0 inch (nominal). Figure 105 shows a typical specimen prior to testing, while figures 106, 107, and 108 present photographs of typical failed specimens. Note that the graphite/epoxy laminates were fabricated as 6- or 8-ply symmetrical sets $[\ ]_S$ and that the scarf joint was formed by the adhesive bonding of these two laminates. This resulted in an effective laminate orientation of $[\ ]_{2S}$. (See figure 105.)

Figures 109 and 110 present the static tension symmetrical scarf joint strengths versus the parameter $2L_a/t$ for titanium to graphite/epoxy adherends of $[0/\pm45]_{2S}$ and $[0_2/\pm45]_{2S}$, respectively. The curves shows that the adhesive shear strength, F_a^S decreases as $2L_a/t$ increases. The trend as indicated by figure 1.3.1-13 of reference 2 shows a constant or even increasing F_a^S with increasing L_a/t. One reason for the graphite/epoxy to titanium bonded scarf joint behavior is that the failure mode was primarily interlaminar shear for the room-temperature specimens leading to a lap shear type behavior with stress decreasing as $2L_a/t$ increases. The elevated temperature data, however, were primarily failure in the adhesive, which shows up as a uniform stress level for the scarf joints tested for both the $[0/\pm45]_{2S}$ and $[0_2/\pm45]_{2S}$ orientations in figures 109 and 110, respectively. It should be noted that even though F_a^S decreases, the joint capacity, N_x (lb/in.) = maximum load/width, increases with lap length, L_a, as shown in tables XXXVIII and XXXIX. The spot check values for $[0/\pm45/90]_{2S}$ orientation bonded to titanium as presented in table XL indicate joint strength values of the same magnitude as the other laminate orientations tested.

The average of the 350°F tension scarf joint strengths was 74 percent of room temperature values (ranges from 48 to 98 percent).

The maximum average joint efficiences attained (at 350°F for the nominal 1-inch scarf lap length) were 0.96 for the $[0/\pm45]_{2S}$ configuration and 0.58 for the $[0_2/\pm45]_{2S}$ configuration. (Refer to tables XXXVIII and XL.)

TABLE XXXVIII GRAPHITE/EPOXY BONDED SYMMETRICAL SCARF JOINT STATIC TENSION DATA $[0/\pm45]_{2S}$

Adherends: Graphite/Epoxy $[0/\pm45]_{2S}$ to Titanium*
Adhesive: Metlbond 329-7

Specimen No.	Temp (°F)	Width (in.)	Thick. t (in.)	Lap Length (in.)	Max Load (lb)	Adhesive Shear Stress (Ksi)	Avg Stress	Failure Mode	Joint Efficiency Avg**
TBGT-6LA-1	RT	0.995	0.093	0.395	2,500	3.18		S	
TBGT-6LA-2	RT	0.995	0.120	0.390	2,695	3.46		S	
TBGT-6LA-3	RT	0.995	0.120	0.395	2,760	3.51	(3.40)	S	(0.53)
TBGT-6LA-4	RT	0.995	0.120	0.395	2,720	3.46		S	
TBGT-6LA-5	350	1.000	0.119	0.385	1,615	2.10		A,S,C	
TBGT-6LA-6	350	0.998	0.120	0.425	1,715	2.02	(2.04)	A,S	(0.39)
TBGT-6LA-7	350	0.999	0.117	0.390	1,565	2.01		A,S	
TBGT-6LB-1	RT	0.870	0.102	0.700	3,300	2.71		T,S	
TBGT-6LB-2	RT	0.872	0.102	0.700	3,225	2.64	(2.69)	T	(0.75)
TBGT-6LB-3	RT	0.871	0.100	0.700	3,320	2.72		T	
TBGT-6LB-4	350	0.878	0.100	0.695	2,390	1.96		C,T	
TBGT-6LB-5	350	0.874	0.100	0.700	2,430	1.99	(2.01)	C,T	(0.69)
TBGT-6LB-6	350	0.875	0.102	0.700	2,545	2.08		S,A	
TBGT-6LC-1	RT	1.001	0.097	1.005	4,320	2.15		T	
TBGT-6LC-2	RT	0.930	0.097	0.990	4,320	2.35	(2.23)	T	(0.88)
TBGT-6LC-3	RT	0.960	0.095	1.000	4,185	2.18		T	
TBGT-6LC-4	350	0.998	0.122	0.995	3,990	2.01		A,T	
TBGT-6LC-5	350	0.999	0.122	0.990	3,860	1.95	(1.98)	T	(0.96)

*Type AS/3002 batch graphite/epoxy to titanium 6Al-4V
**Joint strength/basic laminate strength
NOTE: Failure mode code: A = adhesive; S = laminate interlaminar shear; C = cohesive; T = laminate tension

TABLE XXXIX. GRAPHITE/EPOXY BONDED SYMMETRICAL SCARF JOINT STATIC TENSION DATA $[0/\pm 45/90]_{2S}$

Adherends: Graphite/Epoxy $[0/\pm 45/90]_{2S}$ to Titanium*
Adhesive: Metlbond 329-7

Specimen No.	Temp (°F)	Width (in.)	Thick. t (in.)	Lap Length (in.)	Max Load (lb)	Adhesive Shear Stress (Ksi)	Failure Mode**	Joint Efficiency ***
TBGT-8LA-1	RT	0.996	0.122	0.385	3,520	4.59	S,T.	0.58
TBGT-8LA-2	350	1.001	0.135	0.390	1,735	2.22	S,A	0.33

*Type AS/3002 batch graphite/epoxy to Titanium 6Al-4V
**Failure mode code: A = adhesive; S = laminate interlaminar shear; C = cohesive; T = laminate tension
***Joint strength/basic laminate strength

TABLE XL. GRAPHITE/EPOXY BONDED SYMMETRICAL SCARF JOINT STATIC TENSION DATA $[0_2/\pm 45]_{2S}$

Adherends: Graphite/Epoxy $[0_2/\pm 45]_{2S}$ to Titanium*
Adhesive: Metlbond 329-7

Specimen No.	Temp (°F)	Width (in.)	Thick. t (in.)	Lap Length (in.)	Max Load (lb)	Adhesive Shear Stress (Ksi)	Avg Stress	Failure Mode	Joint Efficiency Avg**
TBGT-8CLA-1	RT	0.999	0.112	0.420	3,480	4.15		S	
TBGT-8CLA-2	RT	0.996	0.115	0.415	4,050	4.90	(4.95)	S	(0.45)
TBGT-8CLA-3	RT	1.000	0.120	0.395	4,230	5.35		S	
TBGT-8CLA-4	RT	1.000	0.119	0.400	4,320	5.40		S	
TBGT-8CLA-5	350	0.998	0.113	0.410	1,425	1.74***		A,S	
TBGT-8CLA-6	350	0.994	0.120	0.465	2,155	2.33	(2.55)	A,S	(0.29)
TBGT-8CLA-7	350	0.997	0.125	0.445	2,450	2.76		A,S	
TBGT-8CLB-1	RT	0.871	0.115	0.700	3,900	3.20		S	
TBGT-8CLB-2	RT	0.870	0.115	0.715	3,765	3.03	(3.08)	S	(0.48)
TBGT-8CLB-3	RT	0.876	0.120	0.704	3,700	3.00		S	
TBGT-8CLB-4	350	0.873	0.120	0.715	2,750	2.20		C,S	
TBGT-8CLB-5	350	0.874	0.120	0.700	2,730	2.23	(2.22)	C,S	(0.41)
TBGT-8CLB-6	350	0.874	0.120	0.715	1,665	1.33***		A,C	
TBGT-8CLC-1	RT	1.000	0.117	1.030	4,765	2.31		S	
TBGT-8CLC-2	RT	0.998	0.112	1.010	4,450	2.21	(2.27)	S	(0.51)
TBGT-8CLC-3	RT	0.999	0.115	1.010	4,620	2.29		S	
TBGT-8CLC-4	350	0.997	0.116	1.000	4,535	2.27	(2.23)	S,C	(0.58)
TBGT-8CLC-5	350	0.994	0.114	1.010	4,380	2.18		C,S	

*Type AS/3002 batch graphite/epoxy to titanium 6Al-4V
**Joint strength/basic laminate strength
NOTE Failure mode code: A = adhesive; S = laminate interlaminar shear; C = cohesive; T = laminate tension
***Premature failure

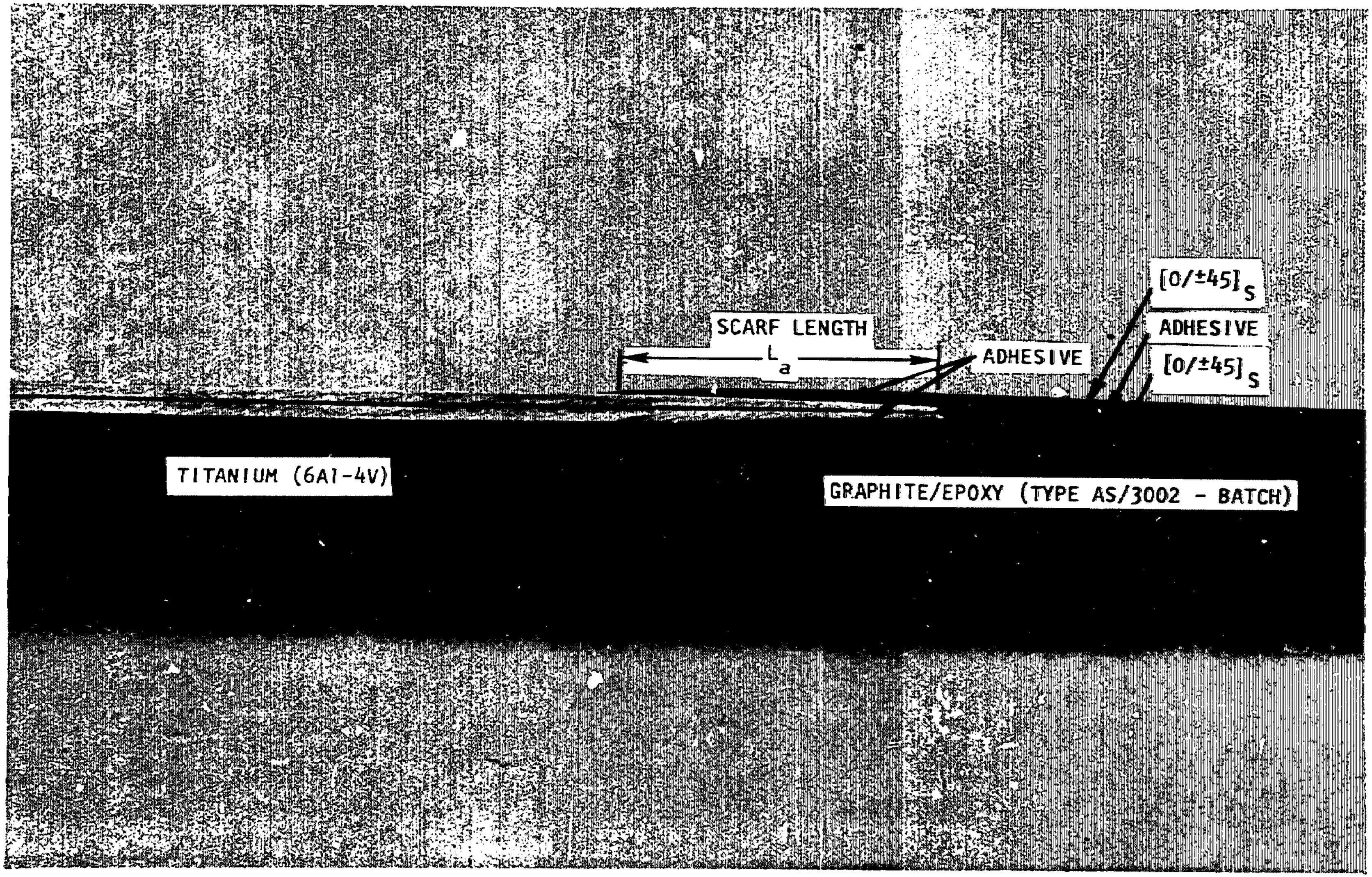


Figure 105. Adhesive-Bonded Tension Scarf Joint - Titanium to Graphite/Epoxy Adherends - Metlbond 329-7 Adhesive

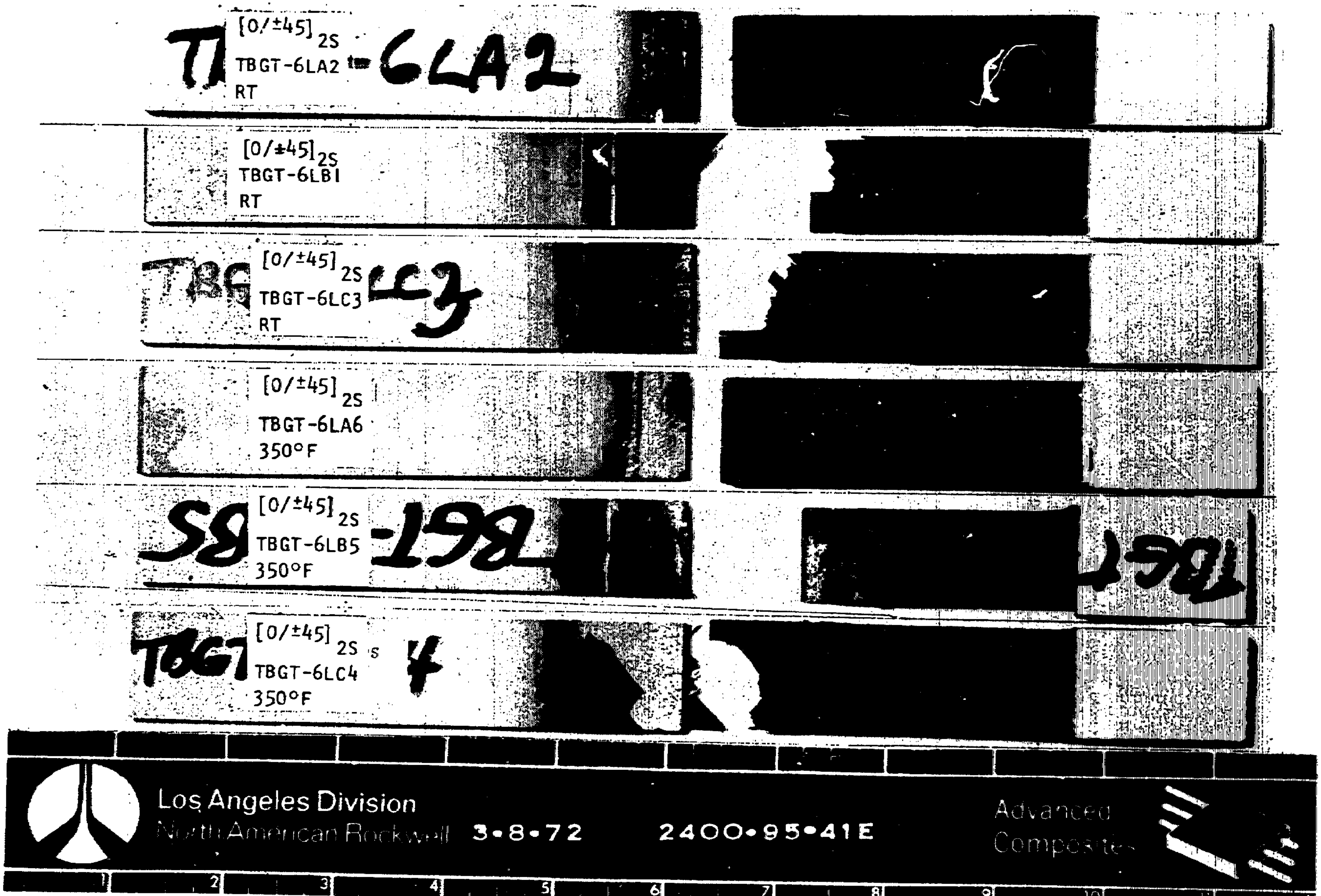


Figure 106. Failed Adhesive-Bonded Tension Symmetrical Scarf Joints - Titanium to $[0/\pm45]_{2S}$ Graphite/Epoxy Adherends - Metlbond 329-7 Adhesive, RT and 350°F

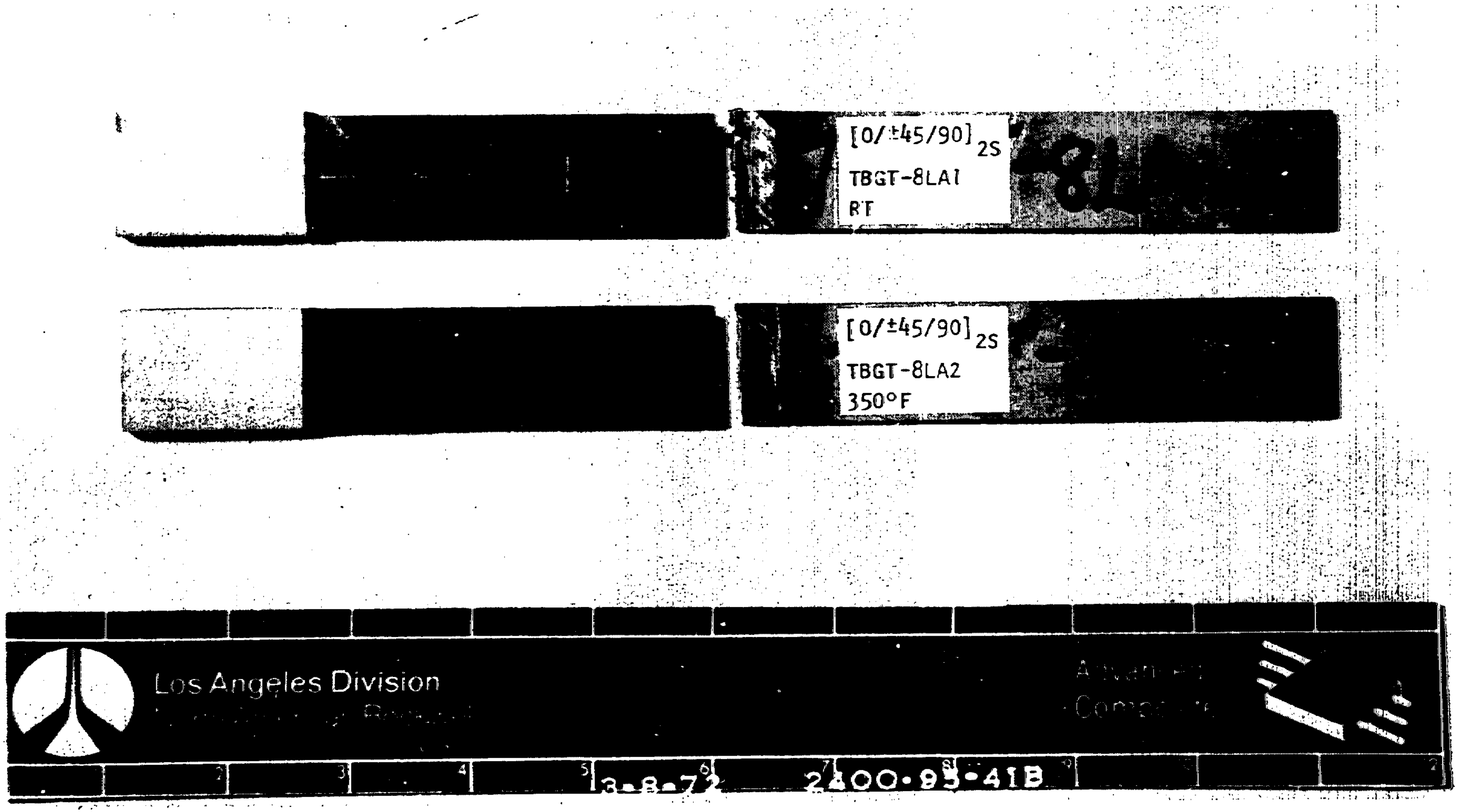


Figure 107. Failed Adhesive-Bonded Tension Symmetrical Scarf Joints - Titanium to $[0/\pm 45/90]_{2S}$ Graphite/Epoxy Adherends - Metlbond 329-7 Adhesive, RT and 350°F

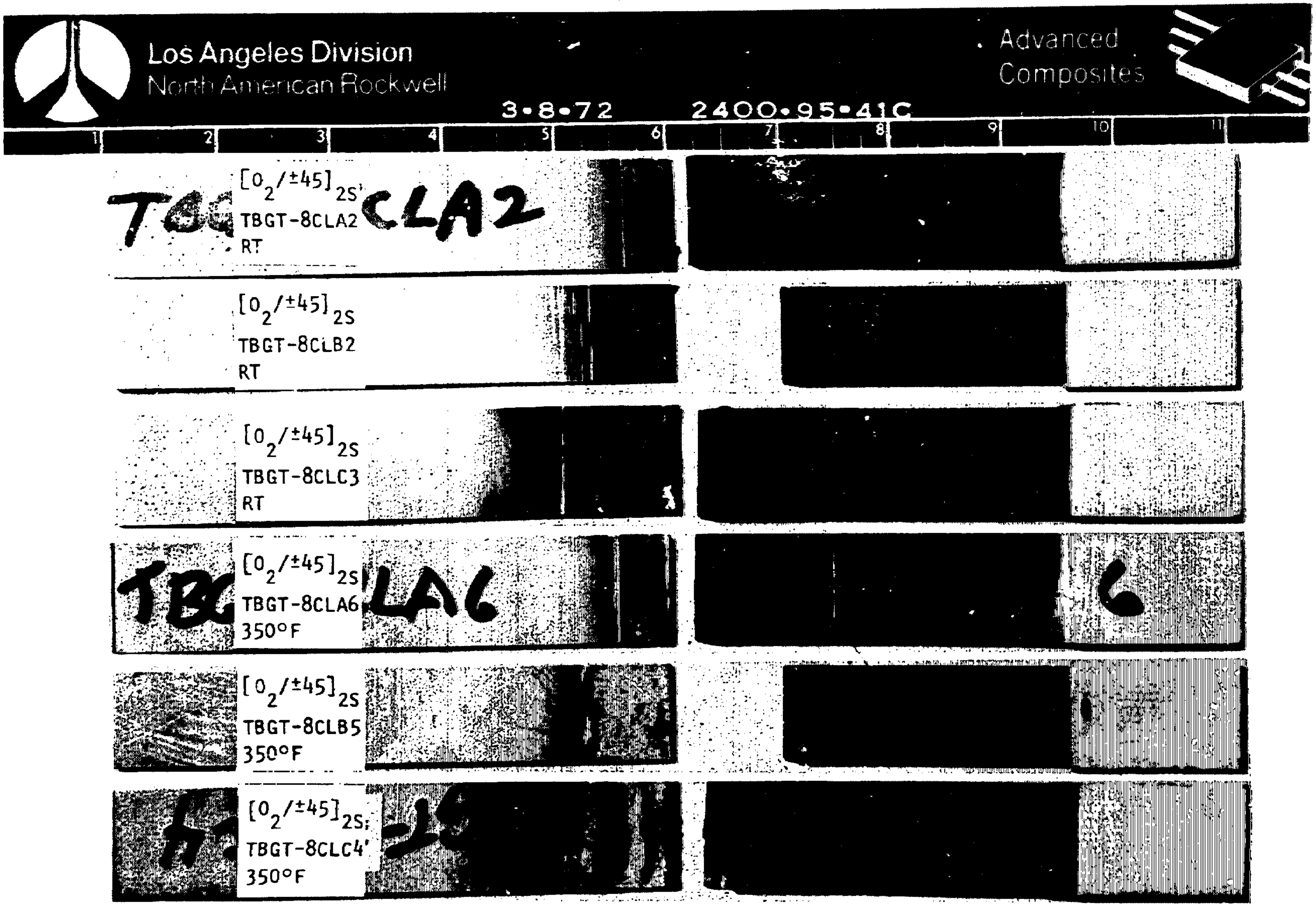


Figure 108. Failed Adhesive-Bonded Tension Symmetrical Scarf Joints - Titanium to $[0_2/\pm45]_{2S}$ Graphite/Epoxy Adherends - Metlbond 329-7 Adhesive, RT and 350°F

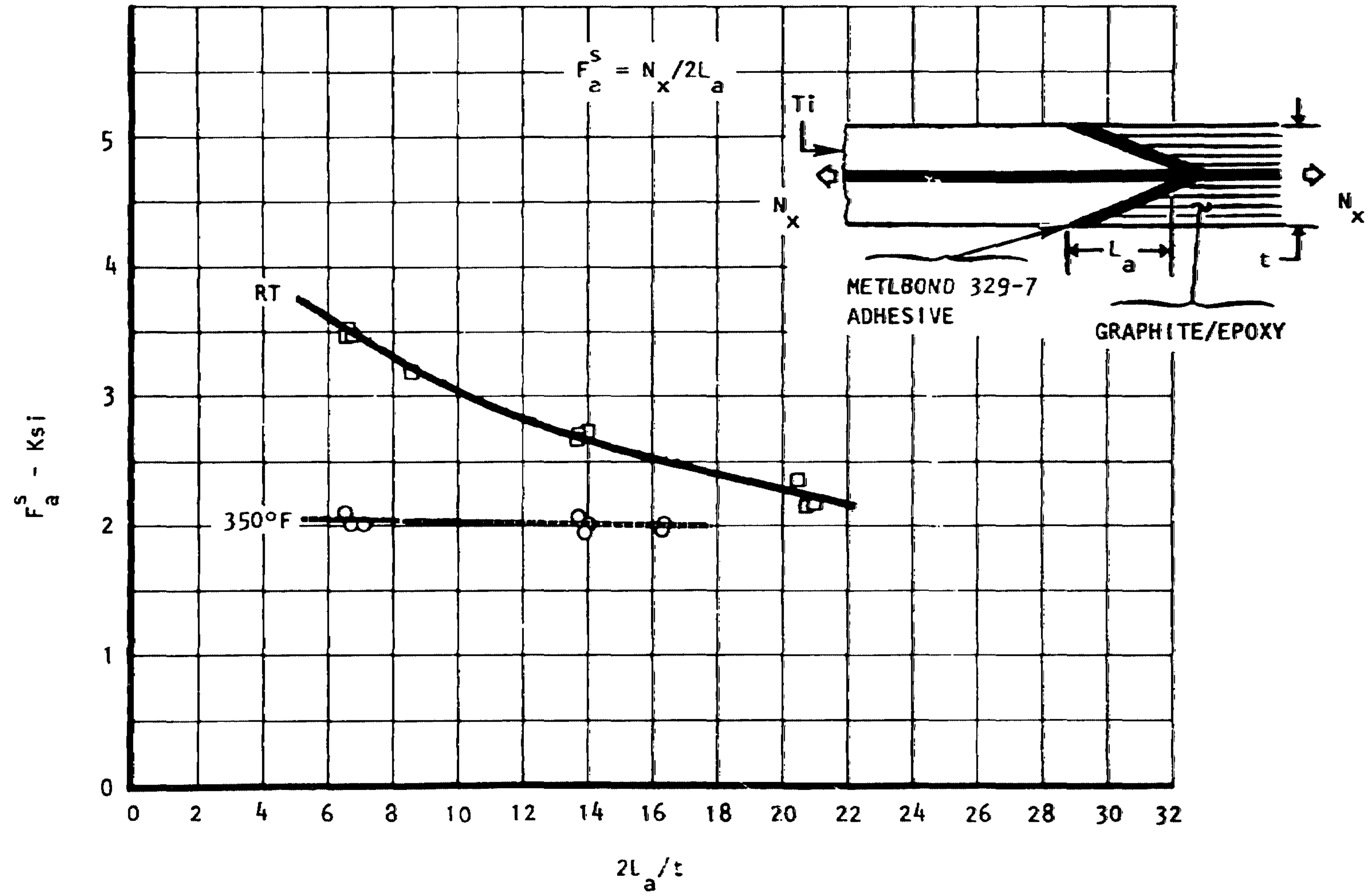


Figure 109. Tension Adhesive Shear Stress Versus Lap Length to Adherend Thickness Ratio for Graphite/Epoxy to Titanium-Bonded Symmetrical Scarf Joints - Type AS/3002 - Batch $[0/\pm45]_{2S}$ Graphite/Epoxy

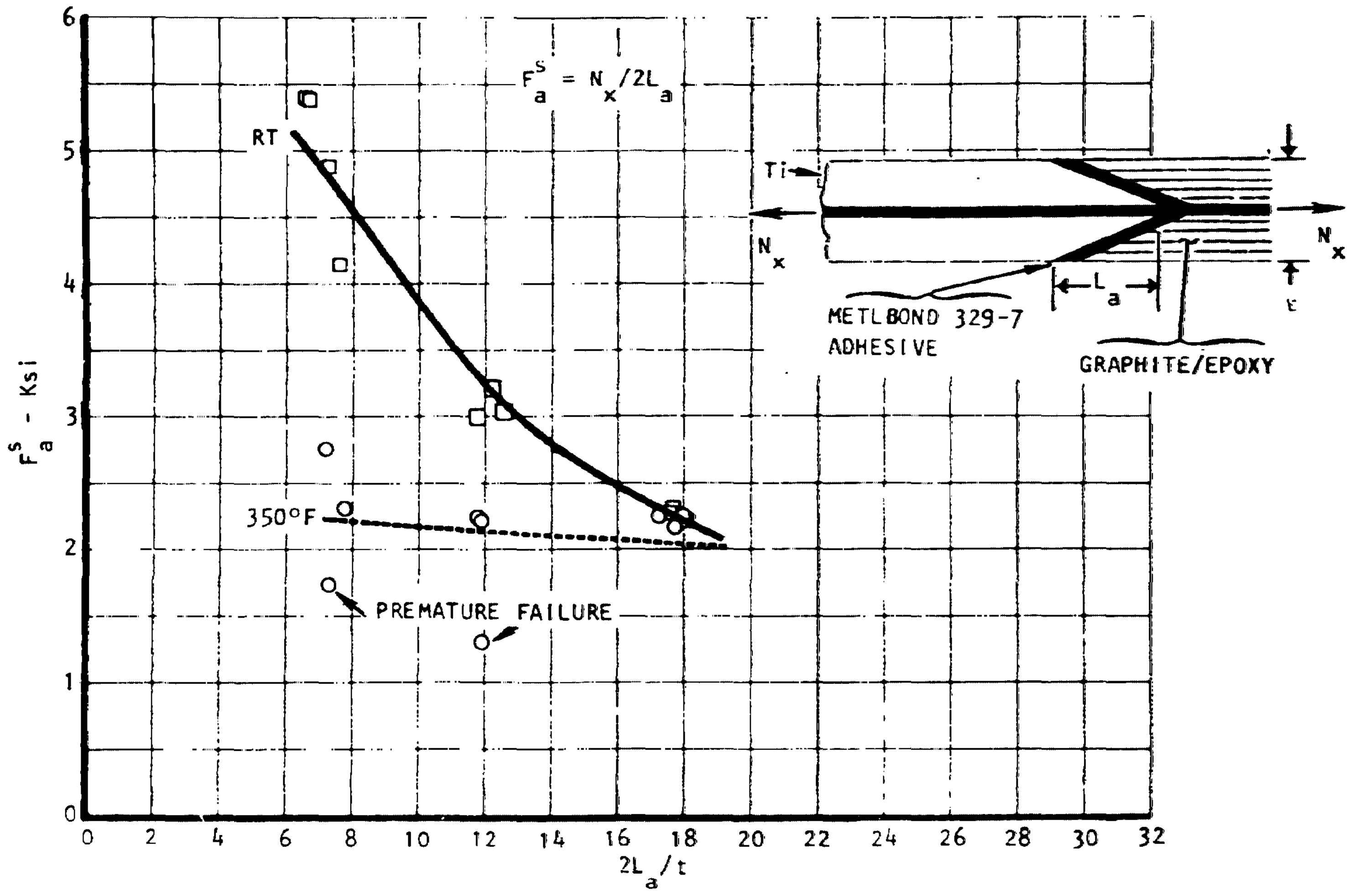


Figure 110. Tension Adhesive Shear Stress Versus Lap Length to Adherend Thickness Ratio for Graphite/Epoxy to Titanium Bonded Symmetrical Scarf Joints - Type AS/3002 - Batch $[0_2/\pm 45]_{2S}$ Graphite/Epoxy

Compression-Loaded Lap Joints

Treated Graphite/Epoxy to Graphite/Epoxy

Bonded (Metlbond 329-7 adhesive) lap joint compression data from edgewise sandwich specimens are presented in table XLI. Three laminate orientations were tested ($[0/\pm45]_S$, $[0_2/\pm45]_S$, $[0/\pm45/90]_S$) with three different lap lengths being tested for each orientation; these being 0.5, 1.0, and 1.5 inch (nominal). Furthermore, both room-temperature and 350°F tests were conducted for each orientation. It was noted, with a few exceptions, that the failure mode was generally one of interlaminar shear in the graphite/epoxy near the joint area. Typical failed specimens are shown in figures 111 and 112.

Figures 113, 114, and 115 present the static compression lap joint data of table XLI in graphical form for the adherend-laminate orientations of $[0/\pm45]_S$, $[0/\pm45/90]_S$, and $[0_2/\pm45]_S$, respectively. The graphite-to-graphite lap joint was stabilized from local compression failure by the sandwich honeycomb core and syntactic foam, so that the failure modes were primarily of interlaminar shear. (See figure 111.) The average adhesive shear strength, F_a^s, had the expected reduction in stress level as the joint parameter L_a/t increased. Also, the 350°F values ranged from 66 to 89 percent of comparable room-temperature values, with an overall average of 74 percent. The 350°F value at $L_a/t = 11.2$ of figure 115, $[0_2/45/90]_S$, was omitted from the average as an obvious premature failure.

Comparison with tension lap joint data from figure 98 $[0/\pm45]_S$, $[0_2/\pm45]_S$, and figure 104 $[0/\pm45/90]_S$, shows that the compression lap joints strengths are significantly improved (at least 50 percent) over that of the tension lap data. This is probably due to the stabilizing influence of the sandwich configuration for the compression loaded specimens over that of the tension peel type loading of the tension lap specimens. For structural applications, stabilized lap joints are recommended so that peel effects are minimized.

Joint efficiency values based on estimated basic compression laminate strengths are shown in the last column of table XLI. These efficiencies are significantly higher than comparable tension single lap data (tables XXXIII, XXXIV, and XXXV).

TABLE XLI. GRAPHITE/EPOXY BONDED LAP JOINT STATIC COMPRESSION DATA FROM EDGEWISE SANDWICH SPECIMENS

Adherends: Graphite/Epoxy to Graphite/Epoxy*
Adhesive: Metlbond 329-7

Orientation	Specimen No.	Temp (°F)	Width w (in.)	Lap Length (in.)	Max Load (lb)	Adhesive Shear Stress (Ksi)	Failure Mode	Basic Laminate F_x^{cu} (Ksi)	Joint Efficiency**
$[0/\pm45]_S$	CLGG-6LA-1	RT	2.923	0.520	10,800	3.56	S	85	0.60
Adherend	CLGG-6LA-2	350	2.980	0.517	9,720	3.16	S	57	0.79
thickness	CLGG-6LB-1	RT	2.969	0.981	14,850	2.55	S	85	0.82
0.036 in.	CLGG-6LB-2	350	2.931	0.995	10,000	1.72	S	57	0.83
	CLGG-6LC-1	RT	2.940	1.507	17,500	1.98	S	85	0.97
	CLGG-6LC-2	350	2.977	1.510	12,725	1.42	S	57	1.04
$[0/\pm45/90]_S$	CLGG-8LA-1	RT	2.889	0.509	10,500	3.57	S	77	0.49
Adherend	CLGG-8LA-2	350	2.937	Tab failed	Tab failed	Tab failed	Tab failed	51	---
thickness	CLGG-8LB-1	RT	2.985	0.957	15,050	1.32	T	77	0.68
0.048 in.	CLGG-8LB-2	350	2.935	0.991	11,325	1.95	S	51	0.79
	CLGG-8LC-1	RT	2.962	1.495	18,100	2.05	S	77	0.83
	CLGG-8LC-2	350	2.958	1.523	14,400	1.60	S	51	0.99
$[0_2/\pm45]_S$	CLGG-8CLA-1	RT	2.938	0.537	17,100	5.42	S	96	0.63
Adherend	CLGG-8CLA-2	350	2.980	0.537	5,910	1.90	S	64	0.32
thickness	CLGG-8CLB-1	RT	2.973	0.995	24,000	4.06	S	96	0.87
0.048 in.	CLGG-8CLB-2	350	2.960	1.008	16,700	2.80	A,C	64	0.92
	CLGG-8CLC-1	RT	2.965	1.548	21,375	2.33	S	96	0.78
	CLGG-8CLC-2	350	2.959	1.507	13,650	1.53	B	64	0.75

NOTE 1. Failure mode code: A = adhesive; B = core to face bond failure; C= cohesive; T = failed under tab;
S = interlaminar shear in laminate

2. Nominal adherend thicknesses based on 0.006 inch ply

*Type AS/3002 batch graphite/epoxy

**Joint strength/basic laminate strength

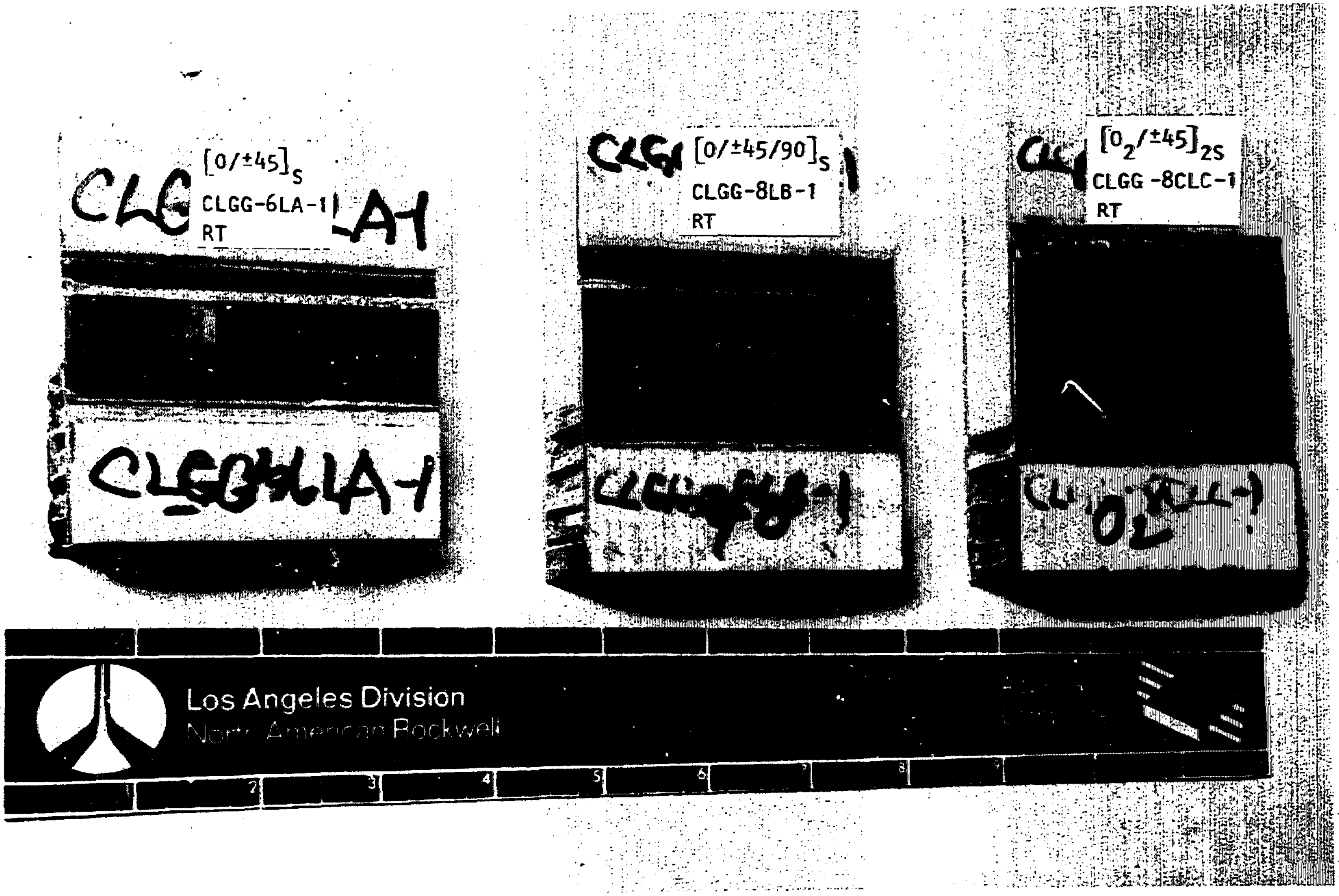


Figure 111. Failed Room Temperature Adhesive-Bonded Lap Joint Compression Test Specimens - Graphite/Epoxy Adherends (Type AS/3002 - Batch), Metlbond 329-7 Adhesive

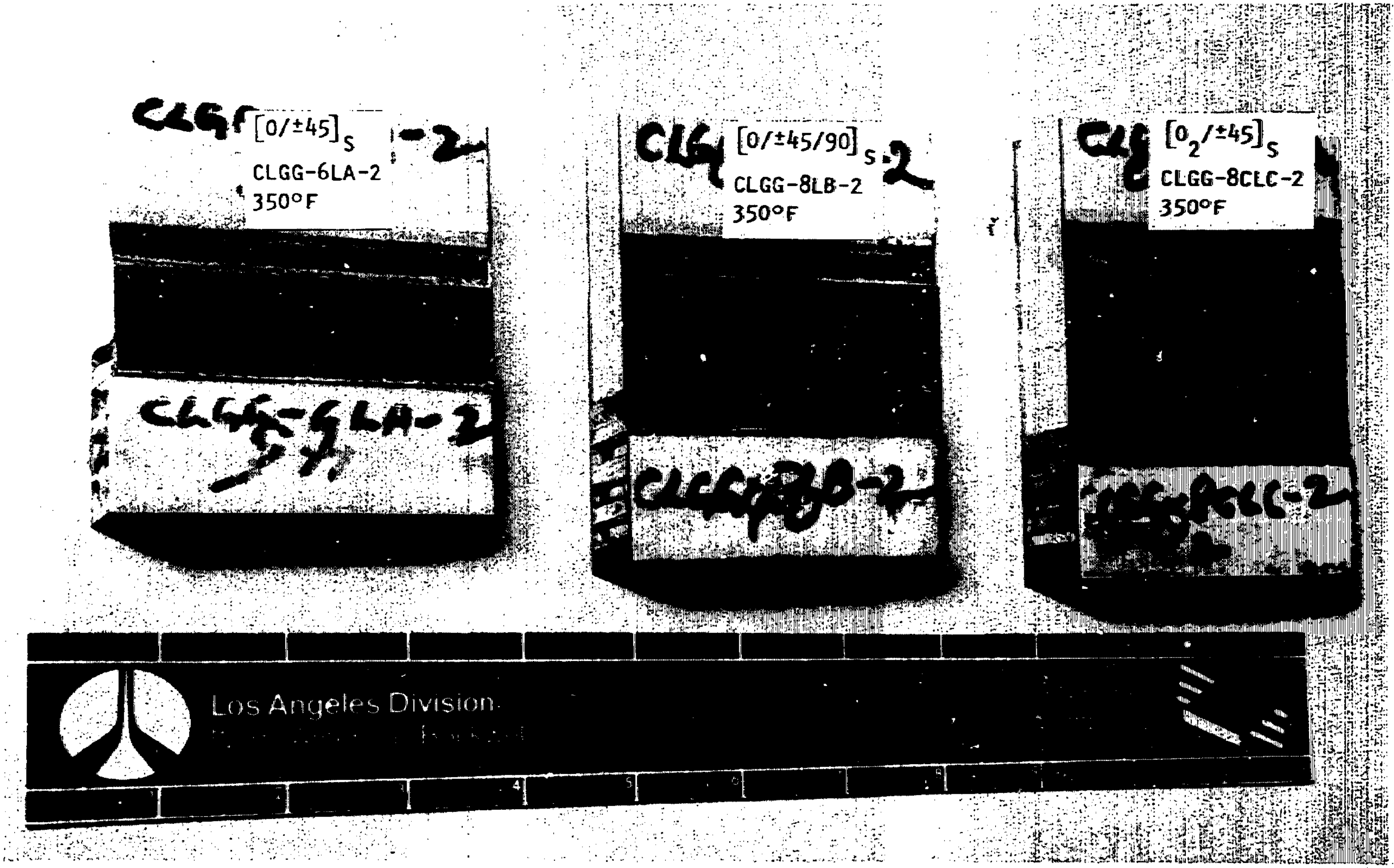


Figure 112. Failed 350°F Adhesive-Bonded Lap Joint Compression Test Specimens - Graphite/Epoxy Adherends (Type AS/3002 - Batch), Metlbond 329-7 Adhesive

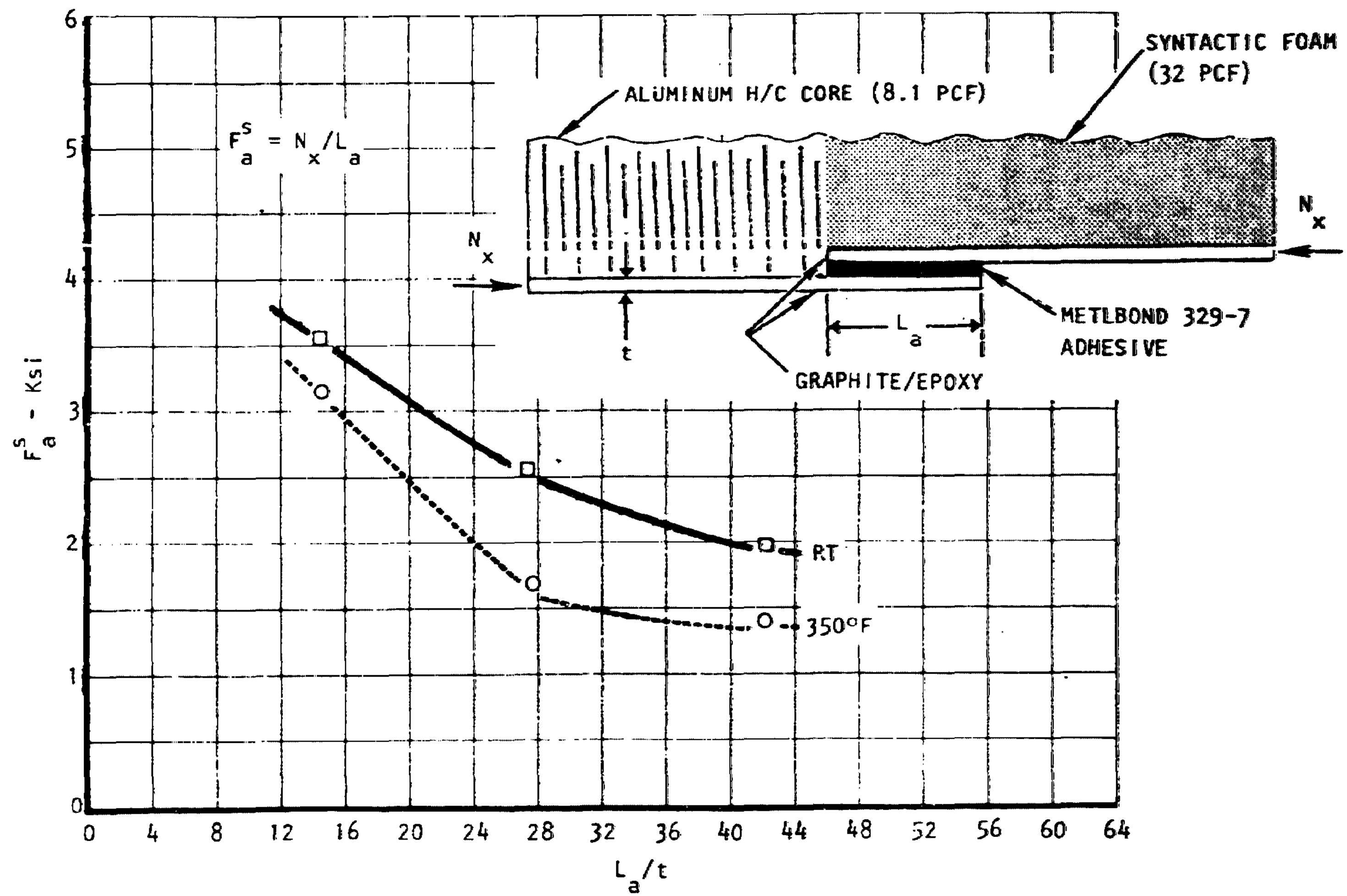


Figure 113. Compression Adhesive Shear Stress Versus Lap Length to Adherend Thickness for Graphite/Epoxy Bonded Single-Lap Joints - Type AS/3002 - Batch $[0/\pm45]_S$ Configuration

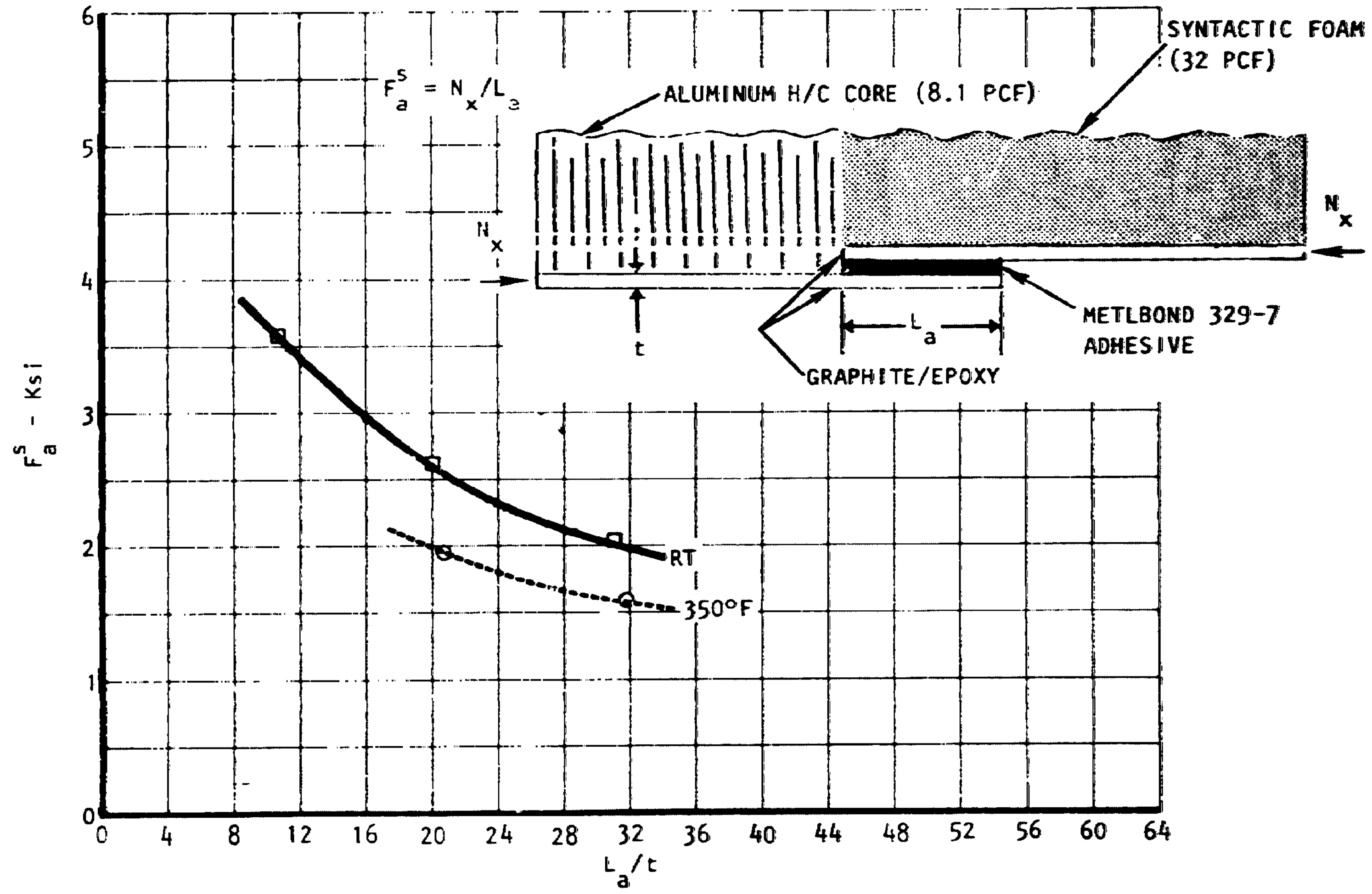


Figure 114. Compression Adhesive Shear Stress Versus Lap Length to Adherend Thickness for Graphite/Epoxy to Graphite/Epoxy Bonded Single-Lap Joints - Type AS/3002 - Batch $[0/\pm 45/90]_S$ Configuration

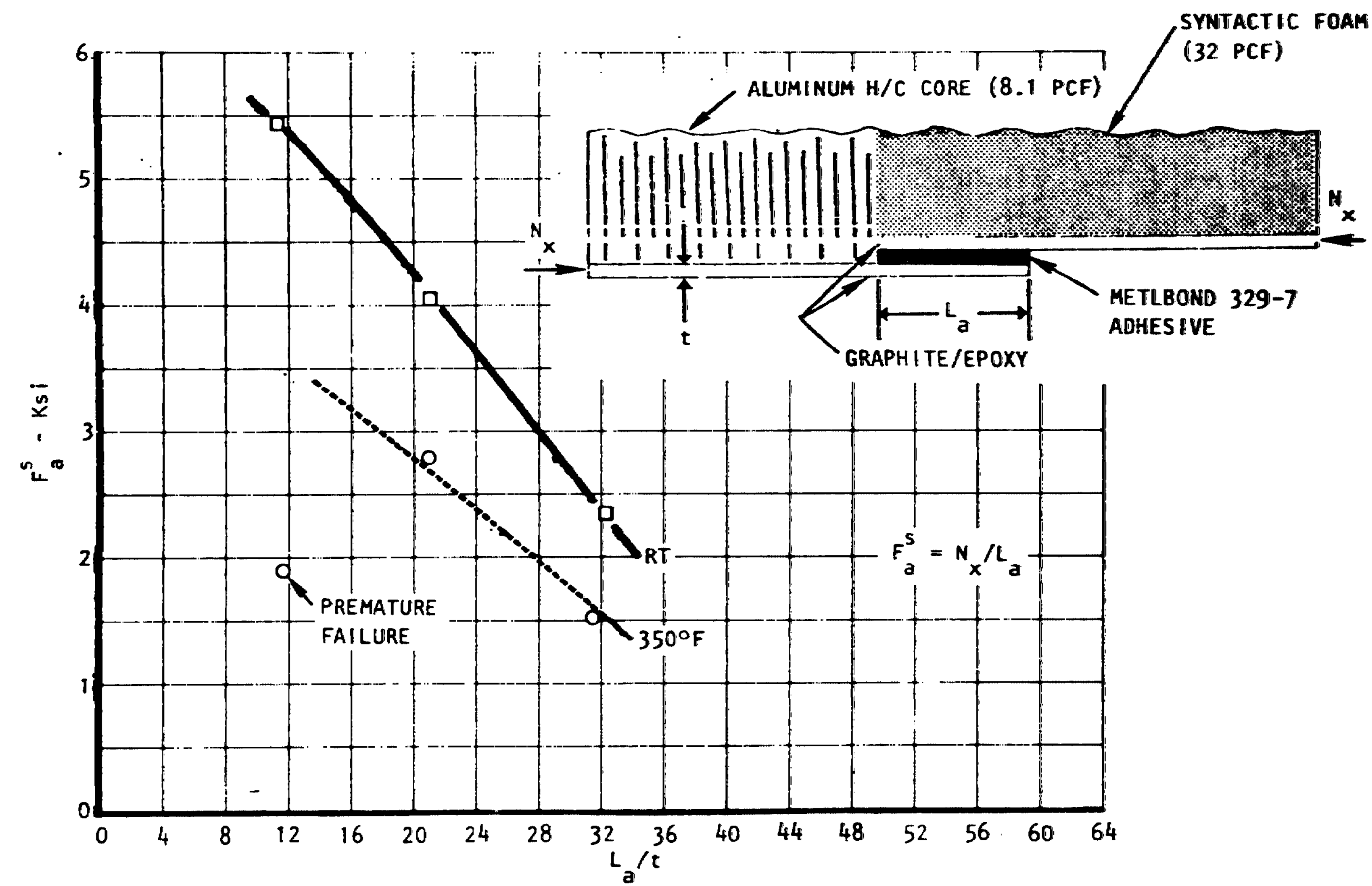


Figure 115. Compression Adhesive Shear Stress Versus Lap Length to Adherend Thickness for Graphite/Epoxy Bonded Single-Lap Joints - Type AS/3002 - Batch $[0_2/\pm 45]_S$ Configuration

Compression-Loaded Symmetrical Scarf Joints

Treated Graphite/Epoxy (Type AS/3002) to Titanium

Test data for bonded (Metlbond 329-7 adhesive) symmetrical scarf joint compression specimens (edgewise sandwich) are shown in Table XLII. Note that $[0/\pm45/90]_{2S}$, $[0/\pm45]_{2S}$, and $[0_2/\pm45]_{2S}$ graphite/epoxy to titanium scarf joints were tested at both room temperature and 350°F. In addition, 0.4-, 0.7-, and 1.0-inch nominal scarf lengths were used for each of the orientations and test temperatures. Typical room-temperature and 350°F failed specimens are pictured in figures 116 and 117, respectively. Note the failure mode column as shown in table XLII.

Figures 118, 119, and 120 present adhesive shear strengths versus $2L_a/t$ for static compression loaded symmetrical scarf joints for titanium bonded to $[0/\pm45]_{2S}$, $[0/\pm45/90]_{2S}$, and $[0_2/\pm45]_{2S}$ orientations, respectively. The scarf joints were stabilized by the sandwich honeycomb core for compressive loading. Comparison of the compression-loaded joints with comparable tension-loaded joints (figures 109 and 110) shows that the compression-loaded bond shear strengths were significantly higher (over 90 percent) than the tension-loaded joints. The strengthening effect of a compression load stress component on the bond rather than a tension component was evident. The elevated temperature values compared with room temperature data show the expected strength reduction (averaged 62 percent of room temperature and a range of 46 to 78 percent of room temperature).

The last column of table XLII shows the joint efficiency attained for the joint configurations shown. The basic laminate compression strengths, F_x^{cu} are estimated values utilizing short column test data and/or extrapolated values, since using the predicted values from section V would yield erroneous efficiencies in excess of unity. Comparison of the efficiencies of compression-loaded scarf joints with the sandwich stabilized lap joints of table XLI shows, in general, there were no significant differences.

TABLE XLII. GRAPHITE/EPOXY BONDED SYMMETRICAL SCARF JOINT COMPRESSION DATA

Adherends: Graphite/Epoxy to Titanium
Adhesive: Metlbond 329-7

Type AS/3002 batch graphite/epoxy
Edgewise compression type specimens

Orientation	Specimen No.	Temp (°F)	Width w (in.)	Scarf Joint Length (in.)	Max Load (lb)	f_x^c Face Sheet Stress (Ksi)	Adhesive Shear Stress (Ksi)	Failure Mode	Joint Efficiency**
$[0/\pm45/90]_{2S}$	CSGT-8LA-1	RT	2.771	0.443	37,100	69.7	7.55	S,L	0.90
	CSGT-8LA-2	350	2.76[illegible]	0.443	19,200	36.1	3.92	S,L	0.71
Face sheet	CSGT-8LB-1	RT	2.753	0.875	41,000	77.6	4.26	S,L	1.01
thickness	CSGT-8LB-2	350	2.752	0.875	22,600	42.8	2.35	S	0.84
0.096 in.*	CSGT-8LC-1	RT	2.748	0.995	33,800	64.1	3.09	S	0.83
	CSGT-8LC-2	350	2.752	0.995	24,000	45.4	2.19	E	0.89
$[0/\pm45]_{2S}$	CSGT-6LA-1	RT	2.753	0.442	30,600	77.2	6.29	S,L	0.91
	CSGT-6LA-2	350	2.748	0.442	16,600	41.9	3.42	A,L	0.73
Face sheet	CSGT-6LB-1	RT	2.745	0.590	30,150	76.3	4.65	A,S	0.90
thickness	CSGT-6LB-2	350	2.685	0.590	21,400	55.3	3.38	S,L	0.97
0.072 in.*	CSGT-6LC-1	RT	2.940	1.001	33,050	78.1	2.81	E	0.92
	CSGT-6LC-2	350	2.745	1.001	19,350	48.9	1.76	E	0.86
$[0_2/\pm45]_{2S}$	CSGT-8CLA-1	RT	2.737	0.319	33,250	63.3	9.52	A,L	0.66
	CSGT-8CLA-2	350	2.753	0.319	15,350	29.0	4.37	S,B	0.45
Face sheet	CSGT-8CLB-1	RT	2.745	0.636	42,800	81.2	6.13	A	0.85
thickness	CSGT-8CLB-2	350	2.741	0.636	33,550	63.7	4.81	S,L	1.00
0.096 in.*	CSGT-8CLC-1	RT	2.745	1.00[illegible]	44,400	84.[illegible]	4.02	S,E	0.88
	CSGT-8CLC-2	350	2.755	1.00[illegible]	30,500	57.8	2.76	E	0.90

NOTE: Failure mode code: A = adhesive bond failure; F = core-to-face bond failure; C = cohesive bond failure;
L = laminate compression buckling; S = interlaminar shear; E = edge failure

*Based on nominal face sheet thickness of 0.006 inch/ply
**Joint strength/basic laminate strength

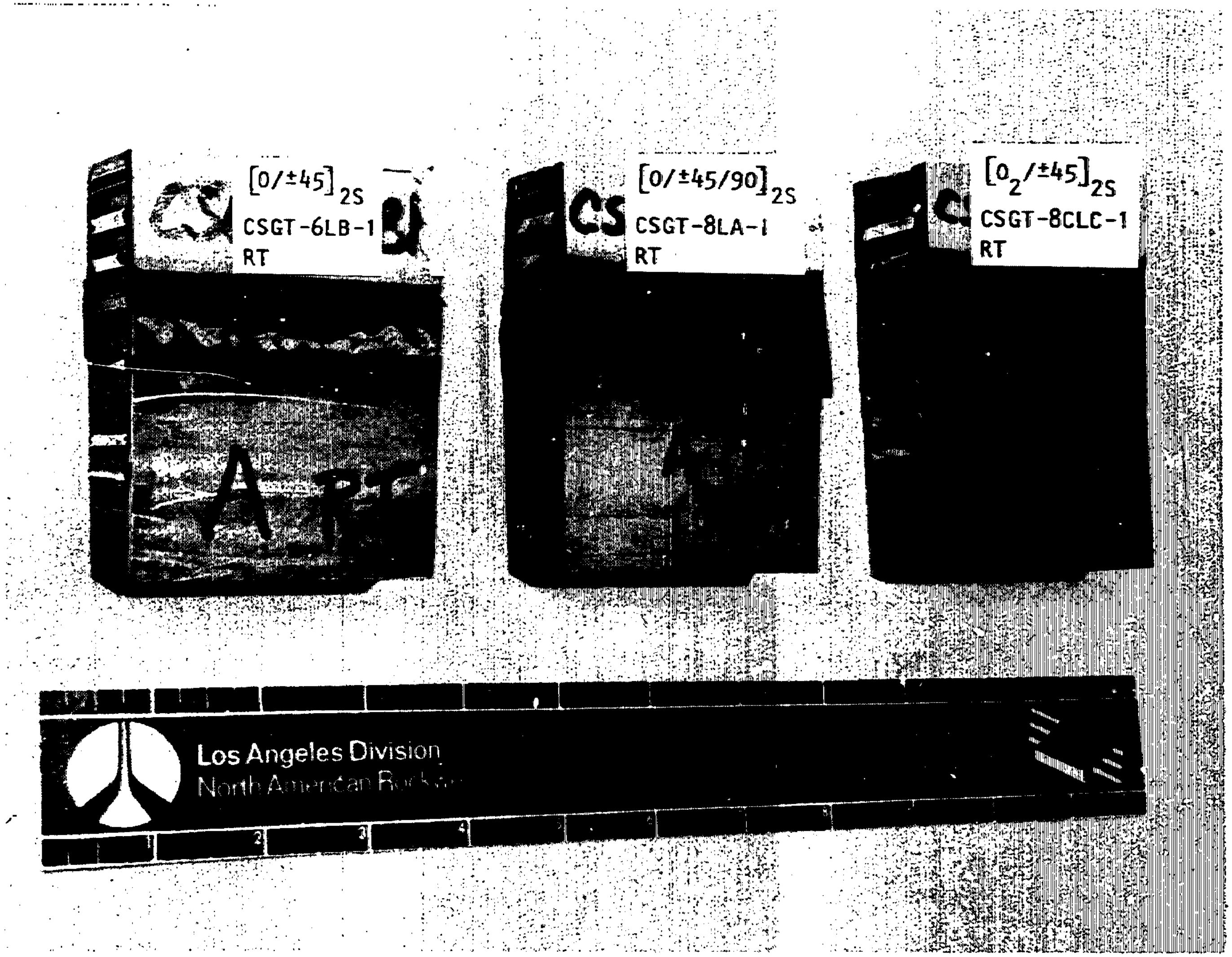


Figure 116. Failed Adhesive-Bonded Compression Scarf Joints - Titanium to Graphite/Epoxy Adherends, Metlbond 329-7 Adhesive, RT

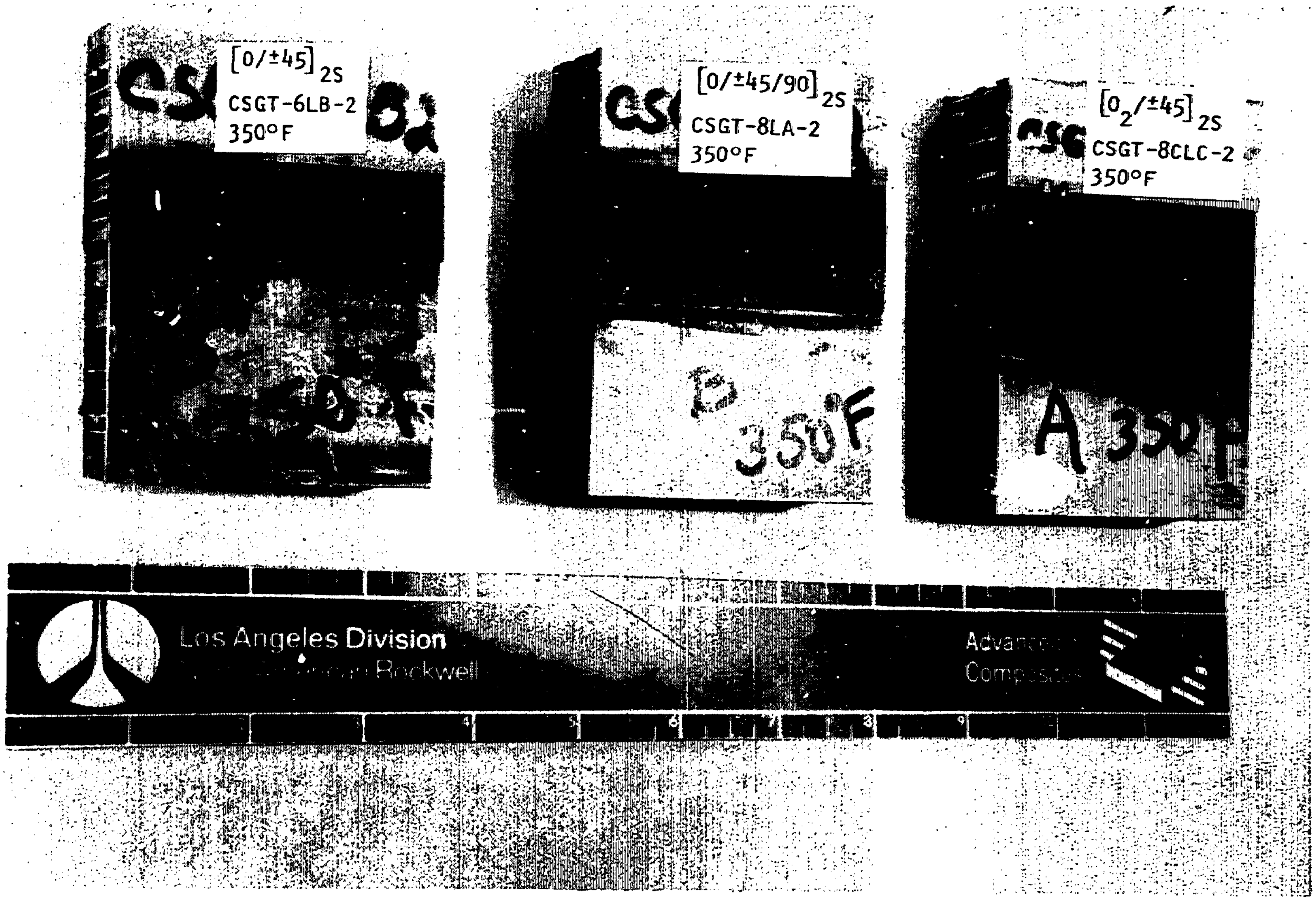


Figure 117. Failed Adhesive-Bonded Compression Scarf Joints - Titanium to Graphite/Epoxy Adherends, Metlbond 329-7 Adhesive, 350°F

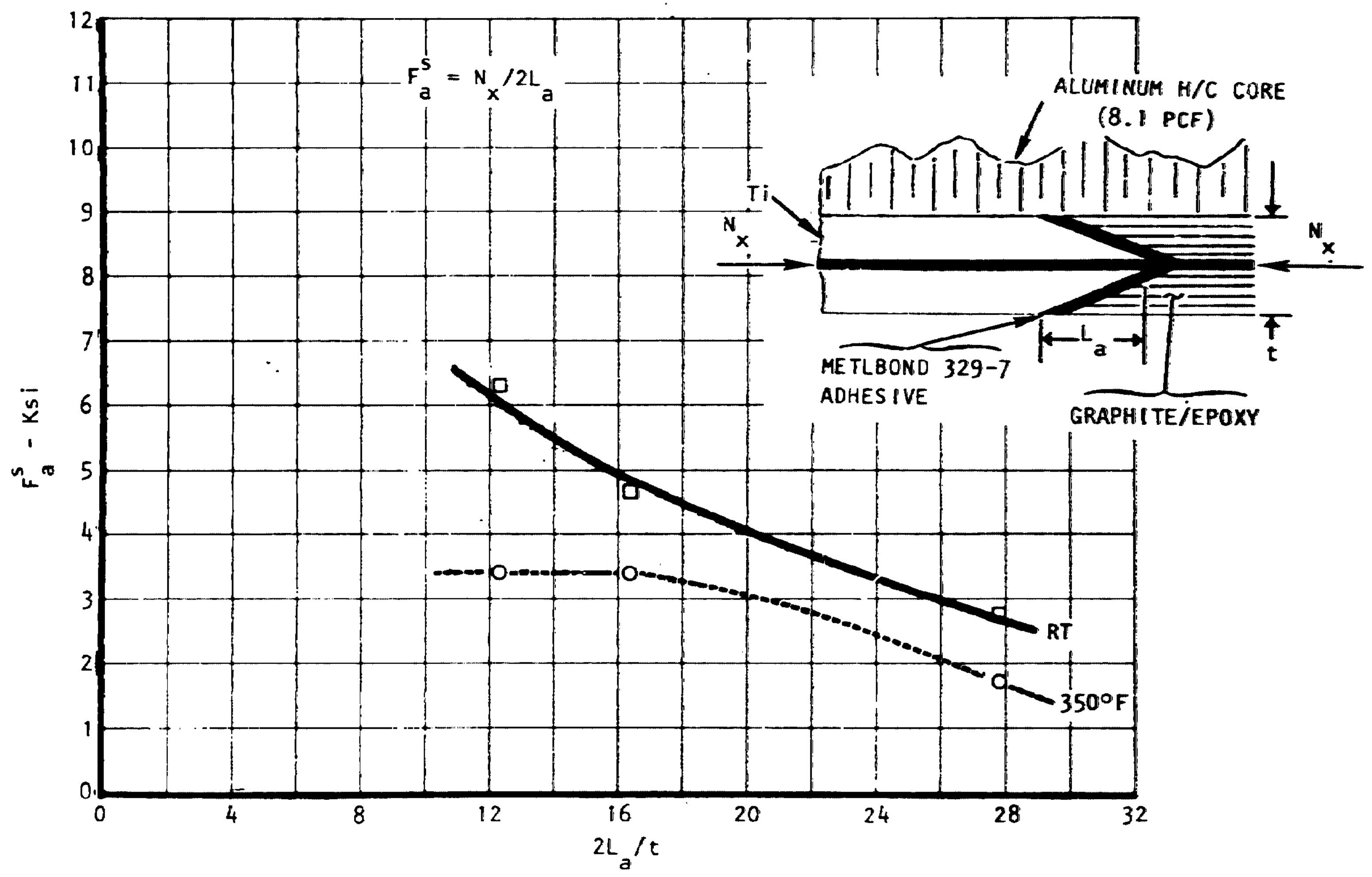


Figure 118. Compression Adhesive Shear Stress Versus Lap Length to Adherend Thickness Ratio for Graphite/Epoxy to Titanium Bonded Symmetrical Scarf Joints - Type AS/3002 - Batch $[0/\pm45]_{2S}$ Graphite/Epoxy

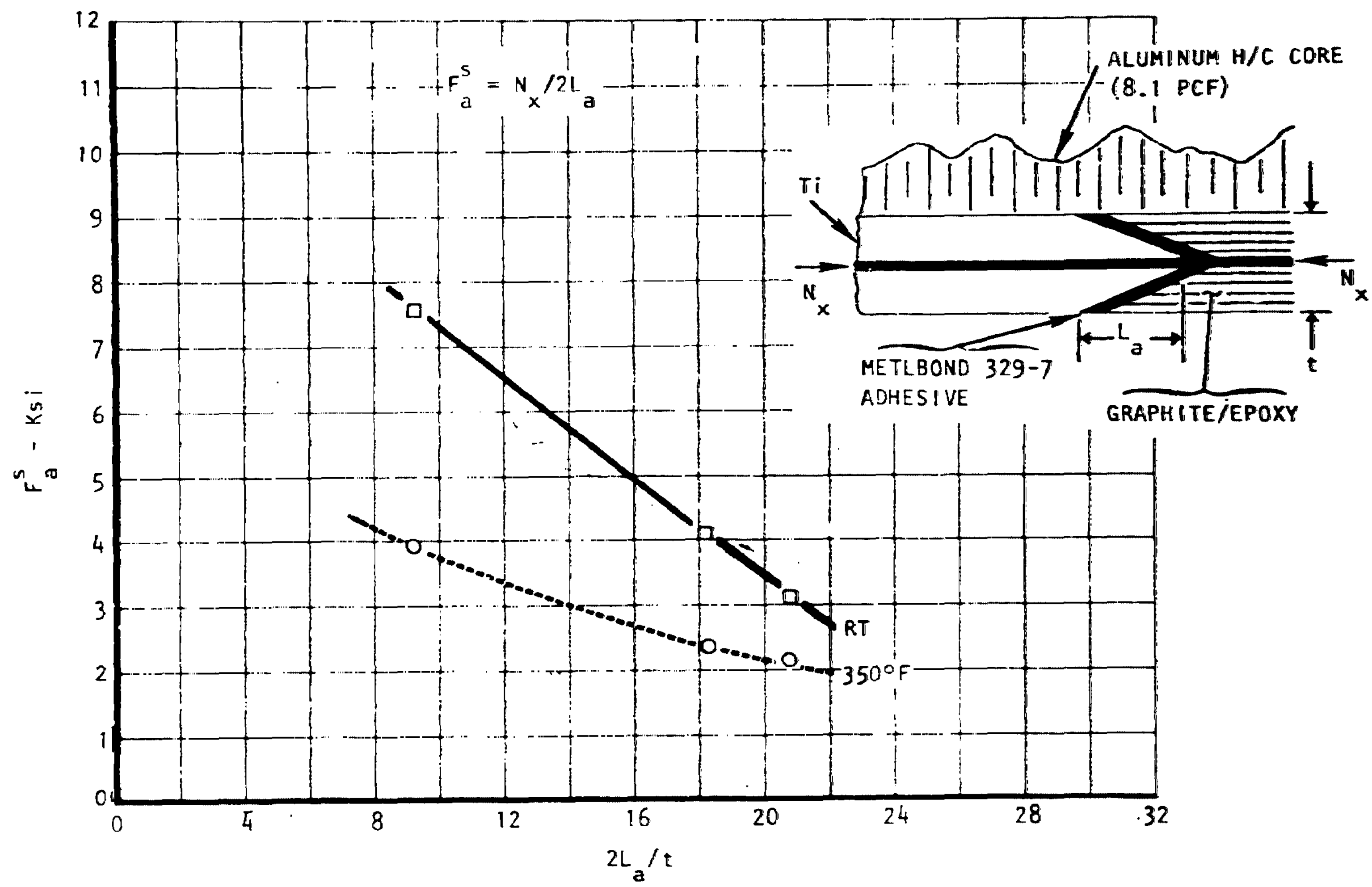


Figure 119. Compression Adhesive Shear Stress Versus Lap Length to Adherend Thickness Ratio for Graphite/Epoxy to Titanium Bonded Symmetrical Scarf Joints - Type AS/3002 - Batch $[0/\pm45/90]_{2S}$ Graphite/Epoxy

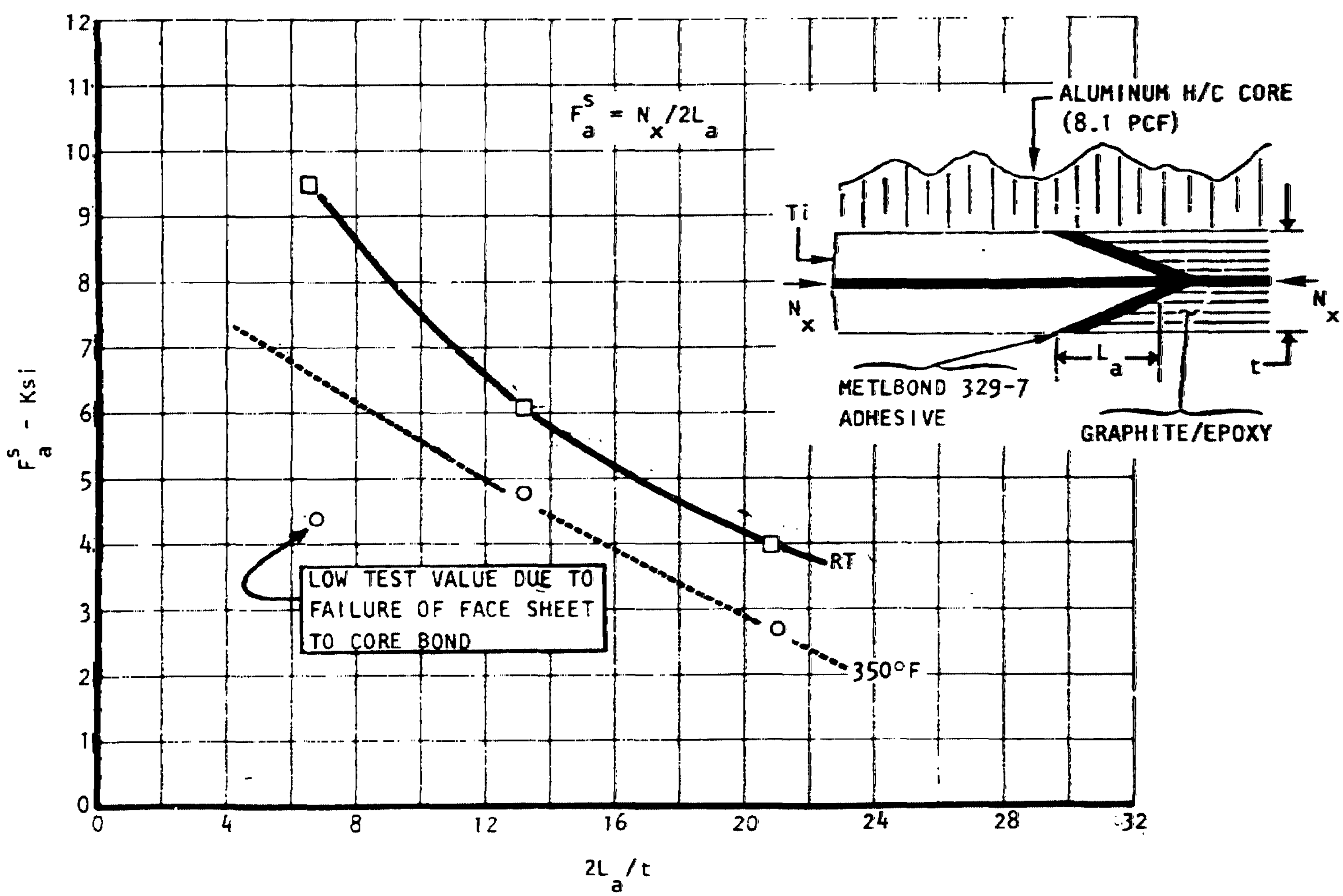


Figure 120. Compression Adhesive Shear Stress Versus Lap Length to Adherend Thickness Ratio for Graphite/Epoxy to Titanium Bonded Symmetrical Scarf Joints - Type AS/3002 - Batch $[0_2/\pm45]_{2S}$ Graphite/Epoxy

Tension Fatigue

Treated Graphite/Epoxy to Graphite/Epoxy (Type AS/3002) Lap Joints

Tables XLIII, XLIV, and XLV summarize constant amplitude tension fatigue data for adhesive-bonded graphite/epoxy single lap joints (Metlbond 329-adhesive). Note that both room-temperature and 350°F specimens were tested. Three different crossplied Type AS/3002 batch graphite/epoxy adherends were tested: $[0/\pm45]_S$, $[0/\pm45/90]_S$, and $[0_2/\pm45]_S$ orientations. All failures that occurred (some specimens were not run to failure because of low test stress levels and, hence, excessively high number of cycles necessary for failure) were interlaminar shear failures. Typical failed specimens are shown in figures 121 and 122. Note, load ratio was 0.05.

The bonded single lap joint tension fatigue data are also plotted in figures 123 and 124. In general, with the exception of a few test points (data scatter), all the data fell into a fairly narrow band. This tends to indicate that the fatigue strength of the bonded lap joints is independent of laminate orientation in laminates with 0° outer plies. Again, as in the static bonded lap joint tests, the failure mode was interlaminar shear in the composite adherends. Note that the nominal lap length was 0.5 inch.

TABLE XLIII. GRAPHITE/EPOXY BONDED LAP JOINT TENSION FATIGUE $[0/\pm45]_S$

Adherends: Type AS/30?2 Batch, $[0/\pm45]_S$ Nominal thickness = 0.036 in.
Adhesive: Metlbond 32? Lap length = 0.5 in.

Specimen No.	Temp (°F)	Width (in.)	Max Cyclic Load (lb)	Max Bond Stress (psi)	Percent of Static (%)	Cycles to Failure*	Failure Mode
BGG-6LA	RT	1.0	1,100	2,200	100	Static	Avg (3)
BGGF-6LA-1	RT	1.000	800	1,600	73	$1x10^3$	L
BGGF-6LA-2	RT	0.989	600	1,213	55	$5x10^3$	L
BGGF-6LA-3	RT	0.990	400	800	37	$71x10^3$	L
BGGF-6LA-4	RT	0.995	300	603	27	$7x10^6$	NF
BGGF-6LA-5	RT	0.992	350	706	32	$6x10^6$	NF
BGGF-6LA-6	RT	0.995	500	1,005	46	$40x10^3$	L
BGG-6LA	350	1.0	980	1,960	100	Static	L Avg (3)
BGGF-6LA-7	350	1.009	700	1,388	71	$1x10^3$	L
BGGF-6LA-8	350	0.990	500	1,010	51	$44x10^3$	L
BGGF-6LA-9	350	0.997	300	602	31	$7.767x10^6$	NF

*Load ratio = 0.05
Note Failure mode code: NF = no failure; A = adhesive; C = cohesive; L = laminate interlaminar shear

TABLE XLIV. GRAPHITE/EPOXY BONDED LAP JOINT TENSION FATIGUE $[0/\pm45/90]_S$

Adherends: Type AS/3002 Batch $[0/\pm45/90]_S$
Adhesive: Metlbond 329-7

Nominal thickness = 0.048 in.
Lap length = 0.5 in.

Specimen No.	Temp (°F)	Width (in.)	Max Cyclic Load (lb)	Max Bond Stress (psi)	Percent of Static (%)	Cycles to Failure*	Failure Mode
BGGF-8LA-1	RT	0.976	945	1,900	---	Static	
BGGF-8LA-2	RT	0.992	985	1,990	---	Static	
BGGF-8LA-3	RT	0.996	935	1,880	---	Static	
			Avg	(1,920)	100	Static	
BGGF-8LA-4	RT	0.998	750	1,503	73	500	L
BGGF-8LA-5	RT	0.998	350	701	37	737	L
BGGF-8LA-6	RT	0.996	250	502	26	3	L
BGG-8LA	350°F	1.0	Est	900	100	Static	C
BGGF-8LA-7	350°F	1.000	650	1,300	144	0	L
BGGF-8LA-8	350°F	0.995	500	1,005	112	57×10^3	L
BGGF-8LA-9	350°F	0.998	300	601	67	6.89×10^6	NF

*Load ratio = 0.05

NOTE Failure mode code: NF = no failure; A = adhesive; C = cohesive; L = laminate interlaminar shear

TABLE XLV. GRAPHITE/EPOXY BONDED LAP JOINT TENSION FATIGUE $[0_2/\pm45]_S$

Adherends: Type AS/3002 Batch, $[0_2/\pm45]_S$
Adhesive: Metlbond 329-7

Nominal thickness = 0.048 in.
Lap length = 0.5 in.

Specimen No.	Temp (°F)	Width (in.)	Max Cyclic Load (lb)	Max Bond Stress (psi)	Percent of Static (%)	Cycles to Failure*	Failure Mode
BGG-8CLA	RT	1.0	670	1,340	100	Static	Avg (3)
BGGF-8CLA-1	RT	0.993	500	1,007	75	$3x10^3$	L
BGGF-8CLA-2	RT	0.995	400	804	60	$78x10^3$	L
BGGF-8CLA-3	RT	1.000	300	600	45	$6.3x10^6$	NF
BGGF-8CLA-4	RT	0.990	350	707	53	$1.23x10^6$	L
BGGF-8CLA-5	RT	0.992	450	907	68	$8x10^3$	L
BGGF-8CLA-6	RT	0.991	550	1,110	83	$4x10^2$	L
BGG-8CLA	350	1.0	807	1,620	100	Static	L Avg (3)
BGGF-8CLA-7	350	0.987	650	1,317	81	$2x10^3$	L
BGGF-8CLA-8	350	0.996	500	1,004	62	$35x10^3$	L
BGGF-8CLA-9	350	0.995	400	804	50	$15x10^3$	L

*Load ratio = 0.05
NOTE Failure mode code: NF = no failure; A = adhesive; C = cohesive; L = laminate interlaminar shear

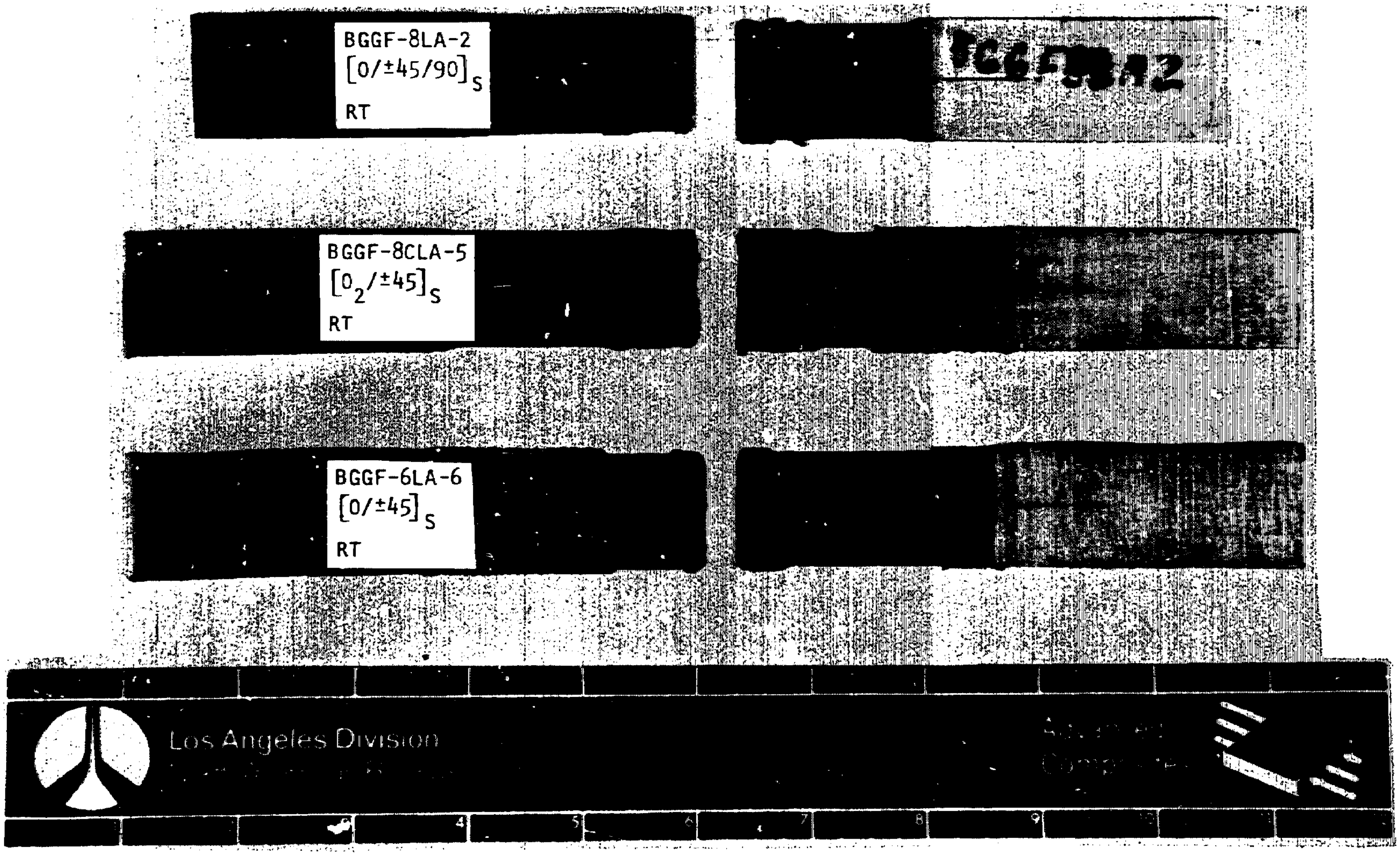


Figure 121. Typical Graphite/Epoxy to Graphite/Epoxy Bonded Single-Lap Joint Tension Fatigue Specimens - RT (Type AS/3002 - Batch) Metlbond 329-7 Adhesive

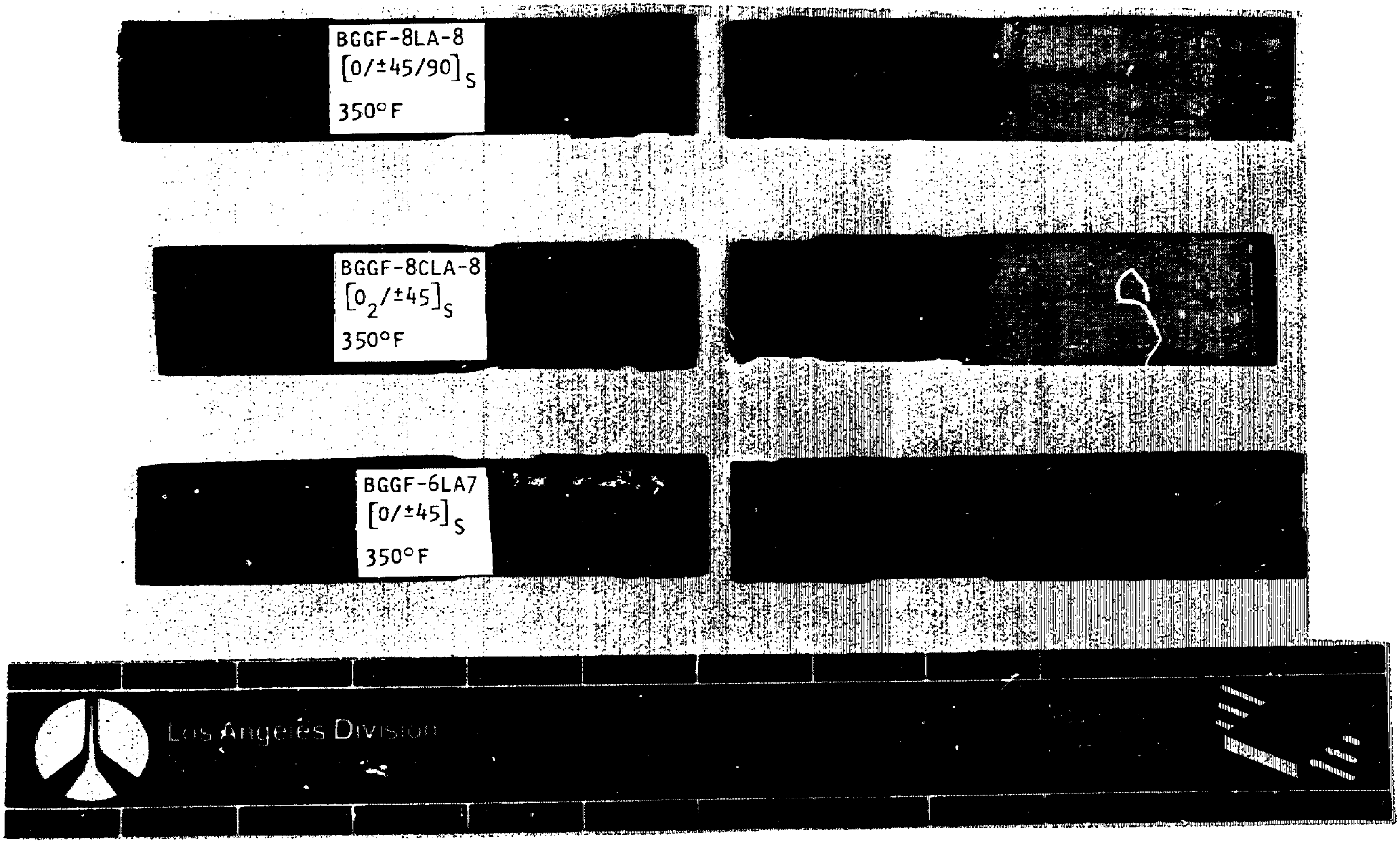


Figure 122. Typical Graphite/Epoxy to Graphite/Epoxy Bonded Single-Lap Joint Tension Fatigue Specimens, 350°F (Type AS/3002 - Batch) Metlbond 329-7 Adhesive

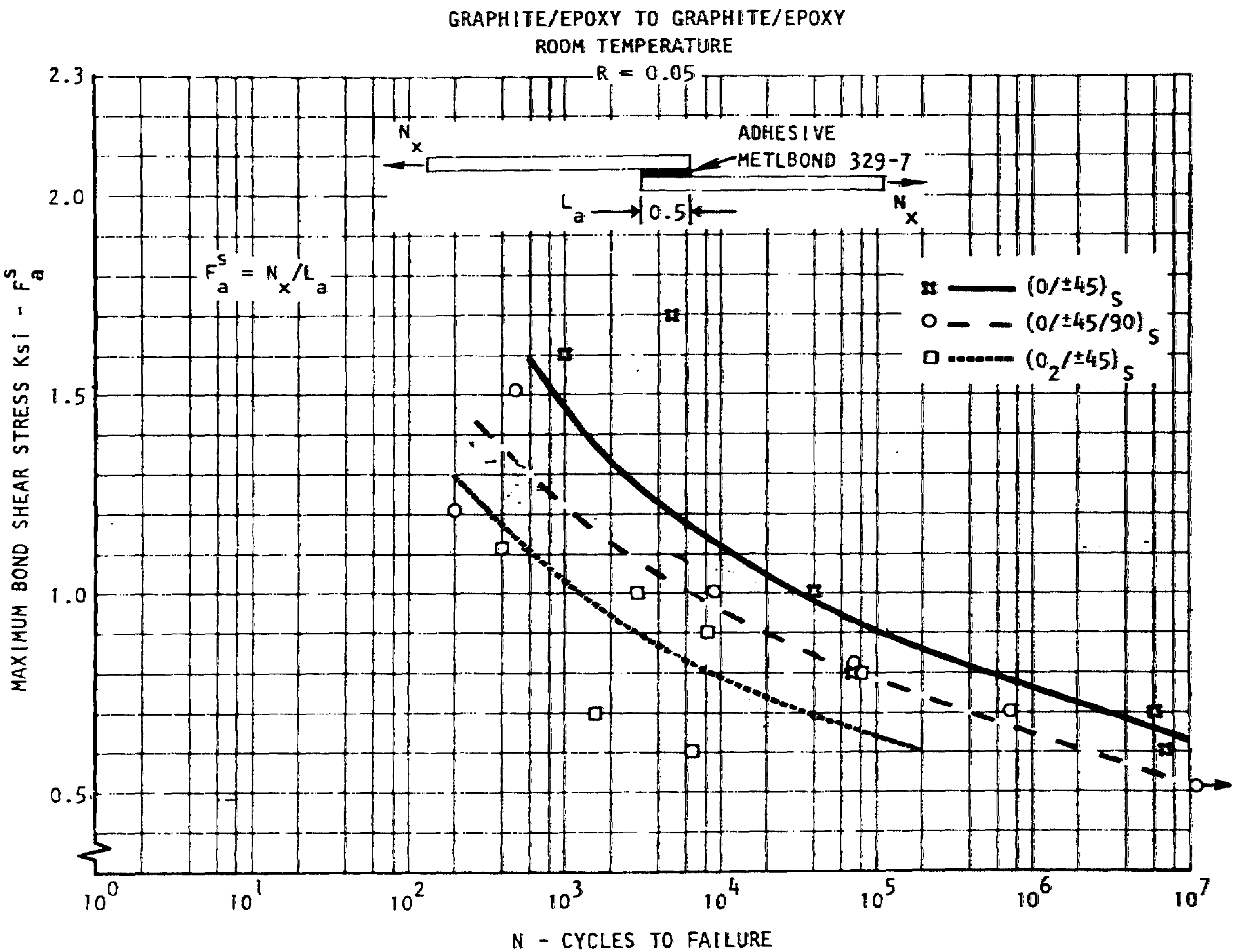


Figure 123. Single-Lap Bonded Joint Tension Fatigue S-N Curve - Type AS/3002 - Batch, Graphite/Epoxy, Room Temperature

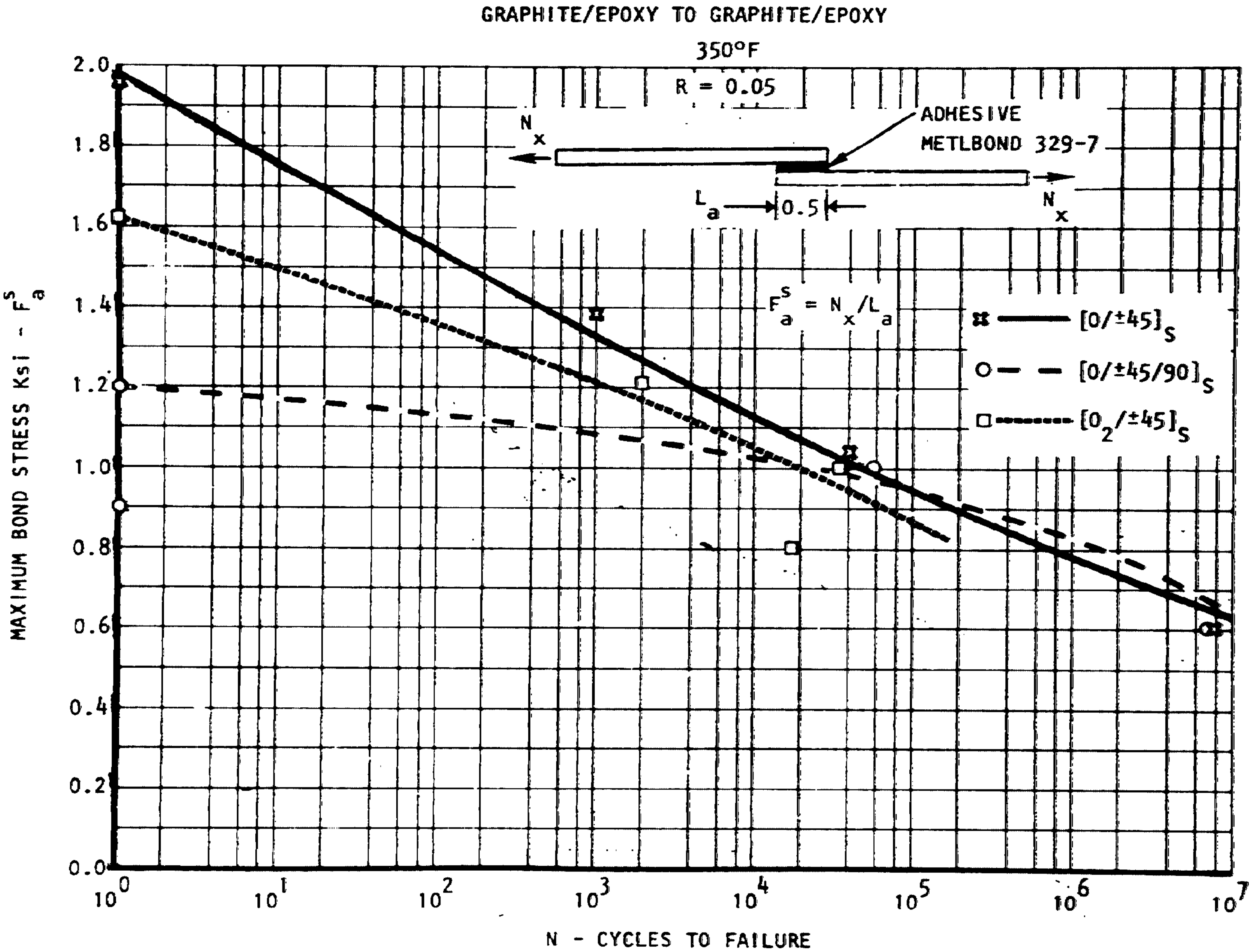


Figure 124. Single-Lap Bonded Joint Tension Fatigue S-N Curve - Type AS/3002 - Batch, Graphite/Epoxy, 350°F

Treated Graphite/Epoxy To Graphite/Epoxy (Type AS/3002) Scarf Joints

Tension fatigue data for bonded symmetrical scarf joints with titanium to Type AS/3002 batch graphite/epoxy adherends (Metlbond 329-7 adhesive) are presented in tables XLVI through XLVIII. Three different orientations were used, including $[0/\pm45]_{2S}$, $[0/\pm45/90]_{2S}$, and $[0_2/\pm45]_{2S}$ with all specimens having a nominal scarf length of 0.4 inch. Both room and elevated (350°F) temperature fatigue tests were conducted. Note that the load ratio used was 0.05.

Photographs of typical failed specimens are shown in figures 125 and 126. While figures 127, 128, and 129 present tension fatigue S-N curves for bonded symmetrical scarf joints with titanium to graphite/epoxy adherends of $[0/\pm45]_{2S}$, $[0/\pm45/90]_{2S}$, and $[0_2/\pm45]_{2S}$ orientations, respectively. Curves and data points for short-time room temperature and 350°F are shown based on the detailed data presented in tables XLVI through XLVIII. The primary failure mode for the fatigue specimens was in the Metlbond 329-7 adhesive, while the baseline static control specimens exhibited laminate interlaminar shear failures at room temperature and adhesive/interlaminar shear failures at 350°F. Comparison of the S-N scarf joint data with the lap joint data shows that the titanium-to-graphite scarf joints exhibit superior performance over that of the graphite to graphite lap joints, not only from a stress level standpoint but also on a percent of static basis.

TABLE XLVI. GRAPHITE/EPOXY BONDED SYMMETRICAL SCARF JOINT TENSION FATIGUE $[0/\pm 45]_{2S}$

Adherends: Titanium to Type AS/3002 Batch $[0/\pm 45]_{2S}$ Graphite/Epoxy
Adhesive: Metlbond 329-7

Specimen No.	Temp (°F)	Width W (in.)	Thick. t (in.)	Scarf Length (in.)	Max Cyclic Load (lb)	Max Bond Stress (psi)	Percent of Static (%)	Cycles to Failure*	Failure Mode
Control**	RT	0.995	0.113	0.394	---	3,400	100	Static	L
TBGTF-6LA-1	RT	0.990	0.098	0.425	2,000	2,354	69	$2x10^3$	A,L
TBGTF-6LA-2	RT	1.004	0.097	0.439	1,700	1,927	57	$91x10^3$	A,L
TBGTF-6LA-3	RT	1.001	0.097	0.439	1,400	1,593	47	$2.58x10^6$	NF
TBGTF-6LA-4	RT	1.004	0.097	0.436	1,550	1,769	52	$7.2x10^5$	A,L
TBGTF-6LA-5	RT	1.001	0.097	0.436	1,850	2,119	62	$5.86x10^5$	A,L
TBGTF-6LA-6	RT	.980	0.098	0.422	1,925	2,328	68	$8x10^3$	A,L
Control**	350	0.999	0.119	0.400	---	2,040	100	Static	A,L
TBGTF-6LA-7	350	0.980	0.099	0.426	1,142	1,368	67	$1x10^3$	A
TBGTF-6LA-8	350	0.980	0.100	0.398	898	1,151	56	$8x10^3$	A
TBGTF-6LA-9	350	0.990	0.090	0.441	653	748	37	$4.04x10^6$	NF

*Load ratio = 0.05
**Control values are the average of test values from static scarf joint specimens.
NOTE Failure mode code: NF = no failure; A = adhesive; C = cohesive; L = laminate interlaminar shear

TABLE XLVII. GRAPHITE/EPOXY BONDED SYMMETRICAL SCARF JOINT TENSION FATIGUE $[0/\pm45/90]_{2S}$

Adherends: Titanium to Type AS/3002 Batch $[0/\pm45/90]_{2S}$ Graphite/Epoxy
Adhesive: Metlbond 329-7

Specimen No.	Temp (°F)	Width W (in.)	Thick. t (in.)	Scarf Length (in.)	Max Cyclic Load (lb)	Max Bond Stress (psi)	Percent of Static (%)	Cycles to Failure*	Failure Mode
Control**	RT	0.996	0.122	0.385	---	4,590	100	Static	L,T
TBGTF-8CL-1	RT	0.950	0.130	0.390	3,000	4,049	88	1	A,L
TBGTF-8LA-2	RT	0.960	0.132	0.392	1,500	1,992	43	3.89×10^5	A,L
TBGTF-8LA-3	RT	0.960	0.126	0.385	2,000	2,706	59	6.3×10^4	A,L
TBGTF-8LA-4	RT	0.980	0.132	0.369	2,500	3,458	75	2.5×10^3	A,L
TBGTF-8LA-5	RT	0.950	0.133	0.389	1,000	1,353	30	2×10^5	NF
TBGTF-8LA-6	RT	0.990	0.133	0.385	1,700	2,231	49	1.07×10^5	A,L
Control**	350	1.001	0.135	0.390	---	2,220	100	Static	A,L
TBGTF-8LA-7	350	0.940	0.130	0.397	1,214	1,627	73	3×10^3	A,L
TBGTF-8LA-8	350	0.990	0.132	0.377	694	929	42	3.04×10^6	NF
TBGTF-8LA-9	350	1.014	0.133	0.390	954	1,206	54	8.73×10^5	A,L

*Load ratio = 0.05

**Control values are the average of test values from static scarf joints specimens.

NOTE Failure mode code: NF = no failure; A = adhesive; C = cohesive; L = laminate interlaminar shear; T = laminate tension

TABLE XLVIII. GRAPHITE/EPOXY BONDED SYMMETRICAL SCARF JOINT TENSION FATIGUE $[0_2/\pm45]_{2S}$

Adherends: Titanium to Type AS/3002 Batch $[0_2/\pm45]_{2S}$ Graphite/Epoxy
Adhesive: Metlbond 329-7

Specimen No.	Temp (°F)	Width W (in.)	Thick. t (in.)	Scarf Length (in.)	Max Cyclic Load (lb)	Max Bond Stress (psi)	Percent of Static (%)	Cycles to Failure*	Failure Mode
Control**	RT	0.999	0.117	0.408	---	4,950	100	Static	L
TBGTF-8CLA1	RT	1.005	0.116	0.460	2,520	2,724	55	6.72×10^5	A,L
TBGTF-8CLA2	RT	1.001	0.126	0.454	2,940	3,234	65	12×10^3	A,L
TBGTF-8CLA3	RT	1.005	0.119	0.452	2,730	3,003	61	3×10^3	***
TBGTF-8CLA4	RT	1.001	0.127	0.447	2,730	3,050	62	1×10^5	A,L
TBGTF-8CLA5	RT	1.003	0.123	0.463	2,394	2,577	52	3.37×10^5	A,L
TBGTF-8CLA6	RT	0.990	0.118	0.455	2,100	2,331	47	2.50×10^6	NF
Control**	350	0.996	0.119	0.440	---	2,550	100	Static	A,L
TBGTF-8CLA7	350	1.002	0.126	0.455	1,407	1,543	61	1×10^4	A
TBGTF-8CLA8	350	1.003	0.129	0.460	1,105	1,197	47	1.46×10^5	A
TBGTF-8CLA9	350	0.985	0.127	0.461	804	886	35	4.7×10^4	A

*Load ratio = 0.05

**Control values are the average of test values from static scarf joint specimens

***Low Test value possibly due to bad joint fabrication

NOTE Failure mode code: NF = no failure; A = adhesive; C = cohesive; L = laminate

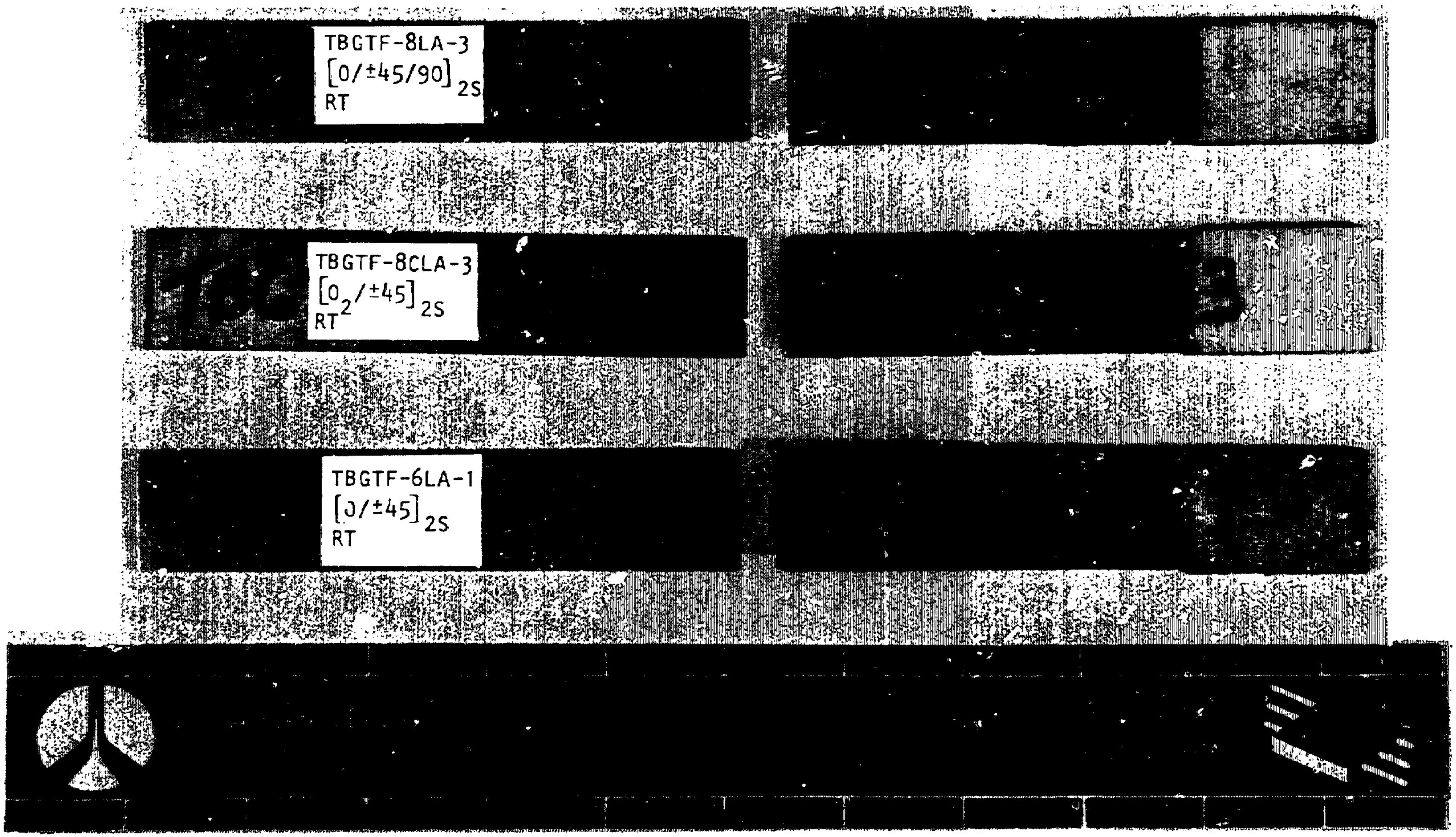


Figure 125. Graphite/Epoxy to Titanium Bonded Symmetrical Scarf Joint Tension Fatigue Specimens - Room Temperature (Type AS/3002 - Batch) Metlbond 329-7 Adhesive

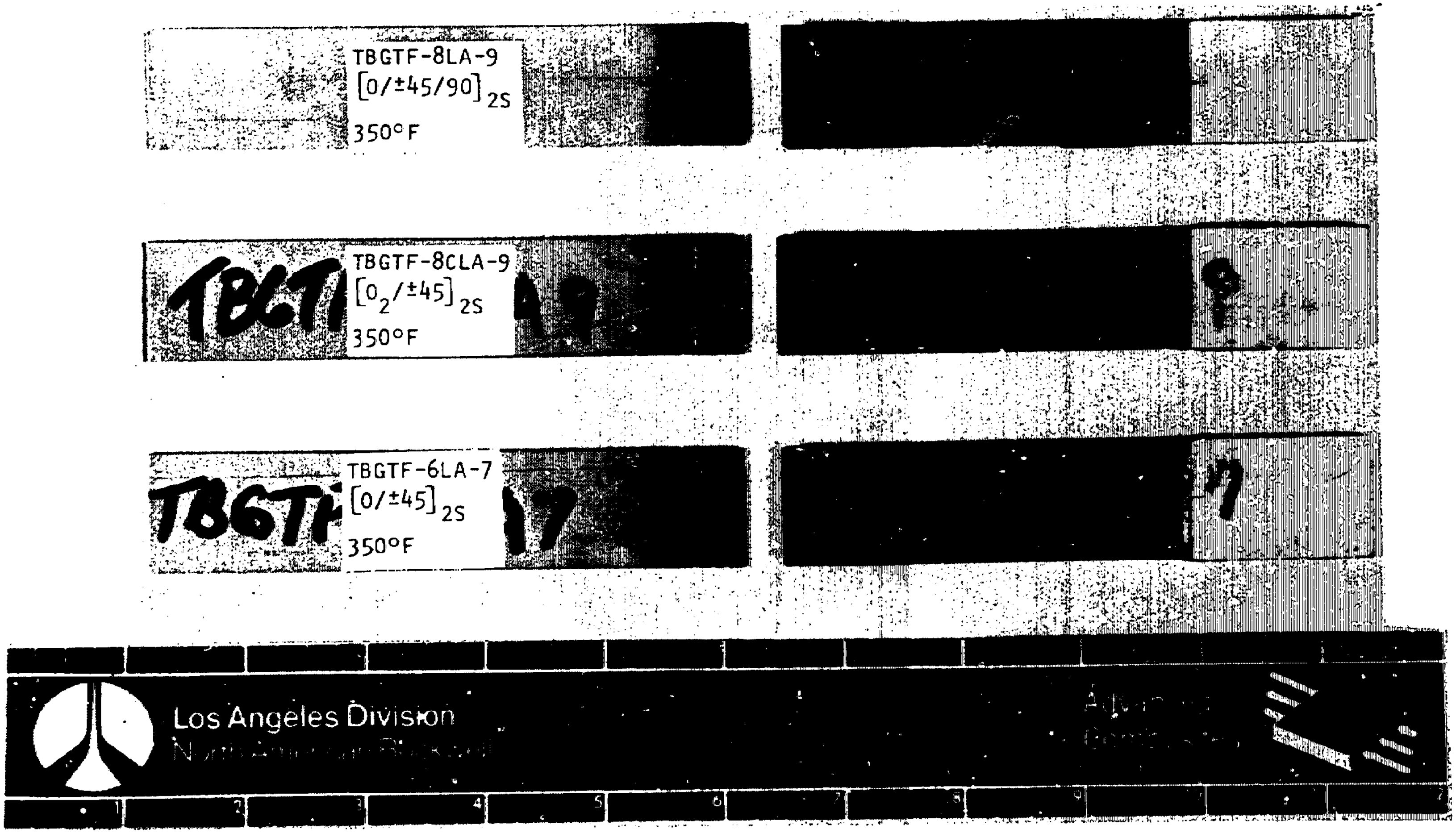


Figure 126. Graphite/Epoxy to Titanium Bonded Symmetrical Scarf Joint Tension Fatigue Specimens - 350°F (Type AS/3002 - Batch) Metlbond 329-7 Adhesive

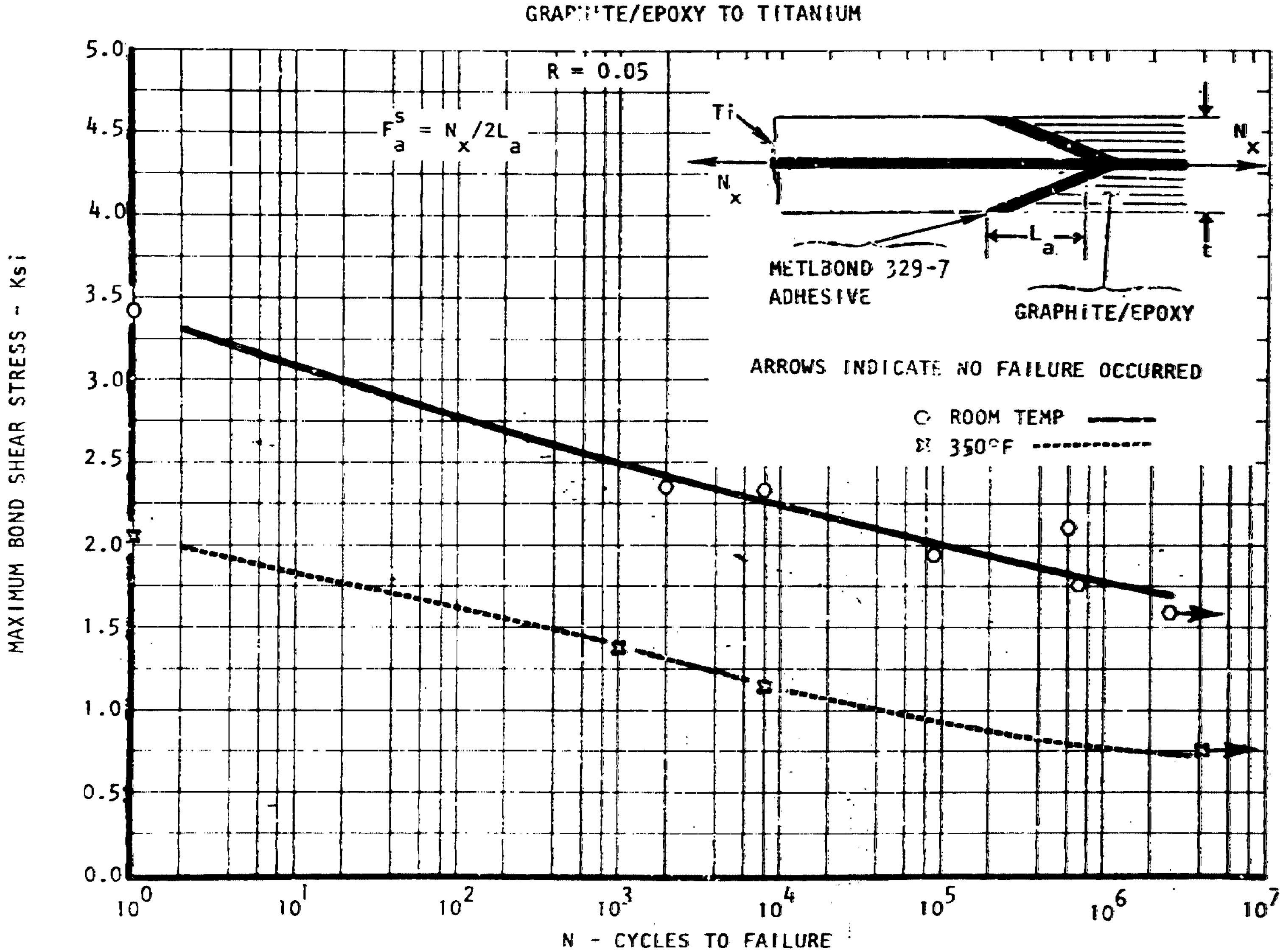


Figure 127. Bonded Symmetrical Scarf Joint Tension Fatigue S-N Curves - Type AS/3002 - Batch, Graphite/Epoxy - Room Temperature and 350°F - $[0/\pm45]_{2S}$

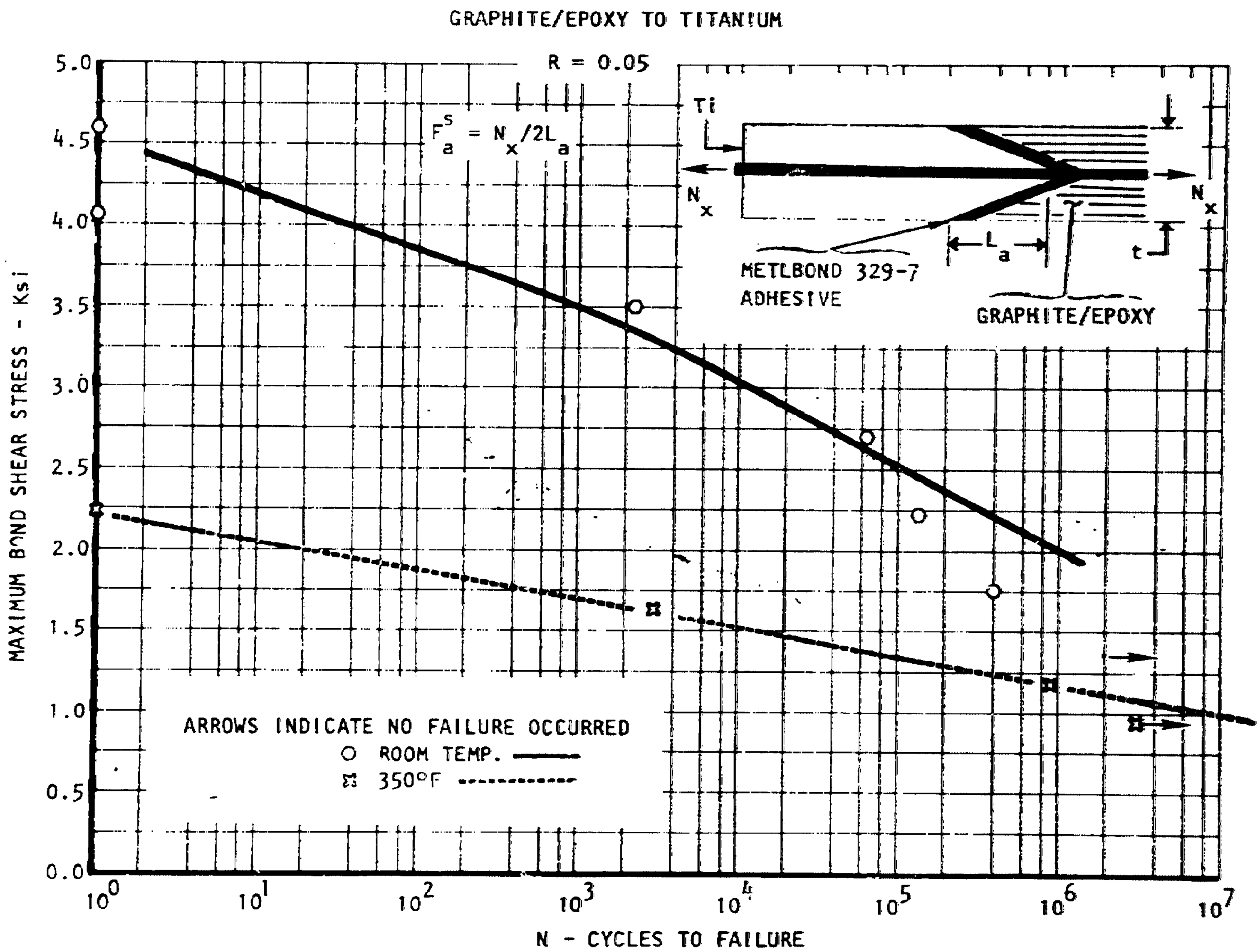


Figure 128. Bonded Symmetrical Scarf Joint Tension Fatigue S-N Curves - Type AS/3002 - Batch, Graphite/Epoxy - Room Temperature and 350°F - $[0/\pm45/90]_{2S}$

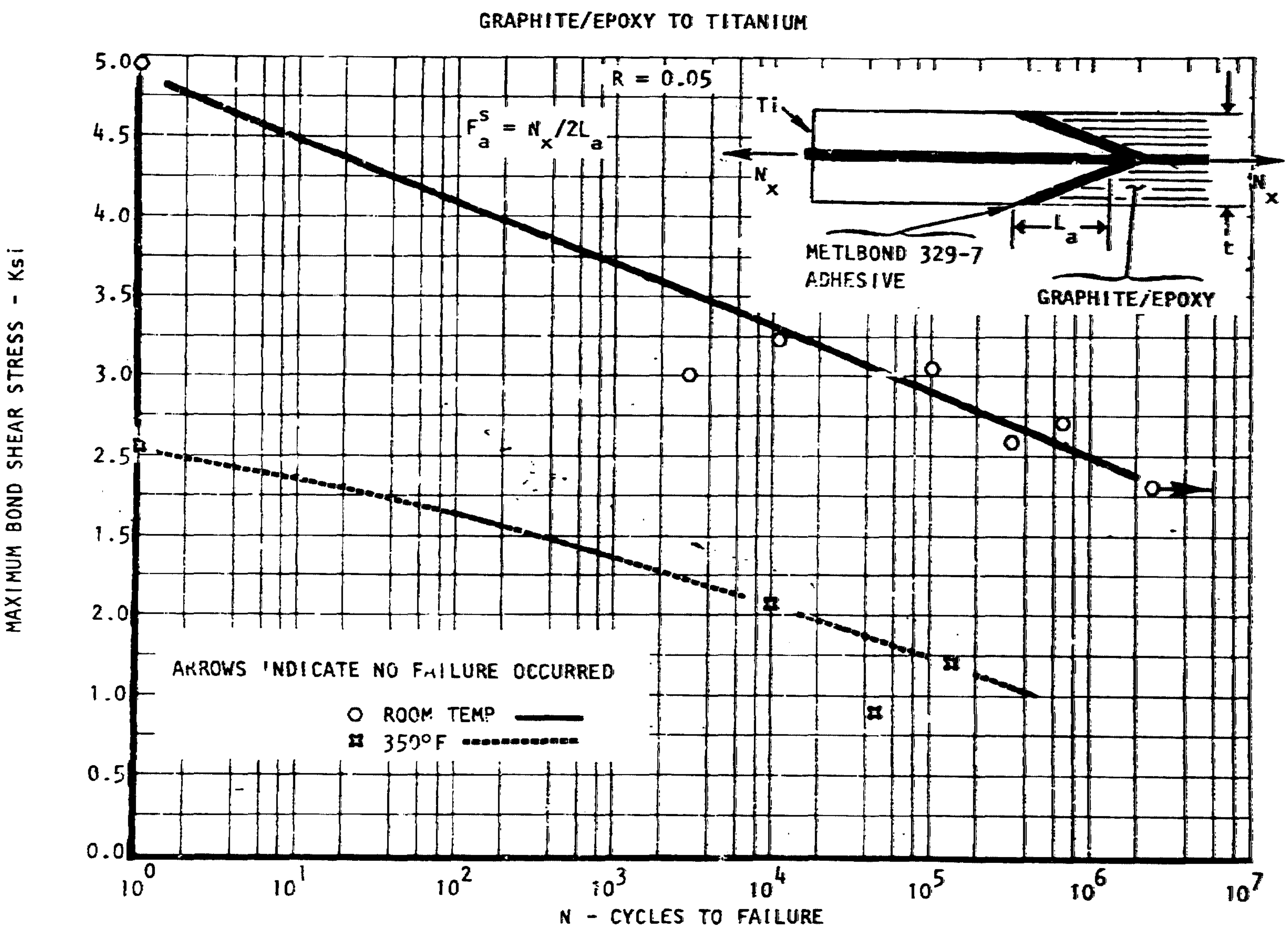


Figure 129. Bonded Symmetrical Scarf Joint Tension Fatigue S-N Curves - Type AS/3002 - Batch, Graphite/Epoxy - Room Temperature and 350°F - $[0_2/\pm45]_{2S}$

MECHANICAL JOINTS

Tension-Loaded Joint - Flush-Head Fastener

Treated Graphite/Epoxy (Type AS/3002) to Steel

Tables XLIX and L present tension data for single lap graphite/epoxy (treated Type AS/3002, batch) to steel mechanical fastened joints tested at -65°F, 70°F (room temperature), and 350°F. NAS 1203 (160,000 to 180,000 psi heat-treat) flush-head fasteners were used for all of the tests. Also, two graphite/epoxy laminate orientations were used, namely $[0/\pm45]_{4S}$ and $[0_2/\pm45]_{2S}$, with three different e/D ratios being tested for each orientation and test temperature (nominal e/D of 2.63, 3.95, and 5.26). All specimens had an s/D ratio of 2.63 (nominal). In general, the failure modes were bearing-type failures, with a few combination bearing/shearout, bearing/net tension failures being observed. Typical failed specimens are shown in figures 130 and 131, which show bearing-type failures occurring on both sides of the specimens.

The joint bearing strengths are plotted in figures 132, 133, and 134 for -65°F, room temperature, 350°F tests, respectively. In all cases, the $[0/\pm45]_{4S}$ graphite/epoxy to steel joints had the higher bearing strength, about 90 Ksi at room temperature and -65°F, and 60 Ksi at 350°F. The $[0_2/\pm45]_{2S}$ graphite/epoxy to steel joints had room temperature and -65°F bearing strengths of about 60 to 70 Ksi, and 350°F strengths of about 45 Ksi (average). In general, there appeared to be little variation in bearing strength due to changes in e/D (for the range tested). The maximum change in F^{br} due to e/D was 20 percent (350°F curve for $[0_2/\pm45]_{2S}$), with most other variations being much less. Note that on figures 132, 133, and 134 there are equations to calculate the equivalent net tension and shearout failure stresses.

In general, then, the following conclusions can be drawn for tension-loaded single lap mechanical joints with flush-head fasteners.

1. There appears to be little variation in bearing strength due to changes in e/D.

2. Bearing strength decreases at elevated temperatures. Bearing strengths at 350°F averaged 34 percent less than room-temperature values.

3. The bearing strength decreases as percentages of 0° plies increases, or as the percent of ±45° plies decreases (for the orientations tested).

4. The flush-head fastener bearing strengths were 25 to 59 percent lower than the average comparable protruding head fastener bearing strengths. (Compare figures 132, 133, and 134, also tables XLIX and L with figures 139, 140, 141, and tables LII and LIII.)

TABLE XLIX. GRAPHITE/EPOXY TO STEEL MECHANICAL FLUSH JOINT SINGLE LAP STATIC TENSION DATA (TYPE AS/3002, BATCH), FASTENER: NAS 1203*, $s/_D$ (NOMINAL) = 2.63, $[0/\pm45]_{4S}$

Specimen Number	Orientation	Temp (°F)	t (in.)	$\frac{e}{D}$	$\frac{D}{t}$	P Test (lb)	F^{br} (Ksi)	F^{tu} (Ksi)	F^{su} (Ksi)	Failure Mode (1)
FHT-24LA1	$[0/\pm45]_{4S}$	70	0.1490	2.63	1.28	2,280	80.54	18.91	18.91	B, S
FHT-24LA2	$[0/\pm45]_{4S}$	70	0.1475	2.63	1.29	2,195	78.32	18.39	18.39	B, T
FHT-24LA3	$[0/\pm45]_{4S}$	350	0.1510	2.63	1.26	1,624	56.61	13.29	13.29	B
FHT-24LA4	$[0/\pm45]_{4S}$	350	0.1470	2.63	1.29	1,644	58.86	13.82	13.82	B
FHT-24LA5	$[0/\pm45]_{4S}$	-65	0.1500	2.63	1.27	2,500	89.47	21.00	21.00	B, S
FHT-24LB1	$[0/\pm45]_{4S}$	70	0.1505	3.95	1.26	2,635	92.15	21.63	13.36	B
FHT-24LB2	$[0/\pm45]_{4S}$	70	0.1480	3.95	1.28	2,410	85.70	20.12	12.42	B
FHT-24LB3	$[0/\pm45]_{4S}$	350	0.1513	3.95	1.26	1,646	57.26	13.44	8.30	B
FHT-24LB4	$[0/\pm45]_{4S}$	350	0.1525	3.95	1.25	1,576	54.39	12.77	7.88	B
FHT-24LB5	$[0/\pm45]_{4S}$	-65	0.1480	3.95	1.28	2,630	93.53	21.96	13.56	B
FHT-24LC1	$[0/\pm45]_{4S}$	70	0.1500	5.26	1.27	2,460	86.32	20.26	9.06	B
FHT-24LC2	$[0/\pm45]_{4S}$	70	0.1505	5.26	1.26	2,345	82.01	19.25	8.61	B
FHT-24LC3	$[0/\pm45]_{4S}$	350	0.1450	5.26	1.31	1,588	57.64	13.53	6.05	B
FHT-24LC4	$[0/\pm45]_{4S}$	350	0.1430	5.26	1.33	1,540	56.68	13.31	5.95	B
FHT-24LC5	$[0/\pm45]_{4S}$	-65	0.1518	5.26	1.25	2,480	85.99	20.19	9.03	B

*150,000 to 180,000 psi heat-treat, flush-head fastener; diameter = 0.19 inch (nominal)

(1) B = bearing, T = net tension, S = shearout

TABLE L. GRAPHITE/EPOXY TO STEEL MECHANICAL FLUSH JOINT SINGLE LAP STATIC TENSION DATA (TYPE AS/3002, BATCH), FASTENER: NAS 1203*, $s/_D$ (NOMINAL) = 2.63, $[0_2/\pm45]_{2S}$

Specimen Number	Orientation	Temp (°F)	t (in.)	$\frac{e}{D}$	$\frac{D}{t}$	P test (lb)	F^{br} (Ksi)	F^{tu} (Ksi)	F^{su} (Ksi)	Failure Mode (1)
FHT-16C-LA1	$[0_2/\pm45]_{2S}$	70	0.1020	2.63	1.86	1,180	60.89	14.29	14.29	B
FHT-16C-LA2	$[0_2/\pm45]_{2S}$	70	0.1040	2.63	1.83	1,236	62.55	14.68	14.68	B
FHT-16C-LA3	$[0_2/\pm45]_{2S}$	350	0.1030	2.63	1.85	668	34.13	8.01	8.01	B
FHT-16C-LA4	$[0_2/\pm45]_{2S}$	350	0.1010	2.63	1.88	768	40.02	9.39	9.39	B
FHT-16C-LA5	$[0_2/\pm45]_{2S}$	-65	0.1040	2.63	1.86	1,174	59.41	13.95	13.95	B,S,T
FHT-16C-LB1	$[0_2/\pm45]_{2S}$	70	0.0980	3.95	1.94	1,492	80.13	18.81	11.61	B
FHT-16C-LB2	$[0_2/\pm45]_{2S}$	70	0.1045	3.95	1.82	1,260	63.46	14.90	9.20	B
FHT-16C-LB3	$[0_2/\pm45]_{2S}$	350	0.1010	3.95	1.88	974	50.76	11.92	7.36	B
FHT-16C-LB4	$[0_2/\pm45]_{2S}$	350	0.1015	3.95	1.87	972	50.40	11.83	7.30	B
FHT-16C-LB5	$[0_2/\pm45]_{2S}$	-65	0.0990	3.95	1.92	1,072	56.99	13.38	8.26	B
FHT-16C-LC1	$[0_2/\pm45]_{2S}$	70	0.1000	5.26	1.90	1,334	70.21	16.48	7.38	B
FHT-16C-LC2	$[0_2/\pm45]_{2S}$	70	0.1025	5.26	1.85	1,300	66.75	15.67	7.01	B
FHT-16C-LC3	$[0_2/\pm45]_{2S}$	350	0.1000	5.26	1.90	810	42.63	10.01	4.48	B
FHT-16C-LC4	$[0_2/\pm45]_{2S}$	350	0.1000	5.26	1.90	732	38.53	9.05	4.05	B
FHT-16C-LC5	$[0_2/\pm45]_{2S}$	-65	0.0960	5.26	1.98	1,220	66.89	15.70	7.03	B

*160,000 to 180,000 psi heat-treat, flush-head fastener; diameter = 0.19 inch (nominal)

(1) B = bearing, T = net tension, S = shearout

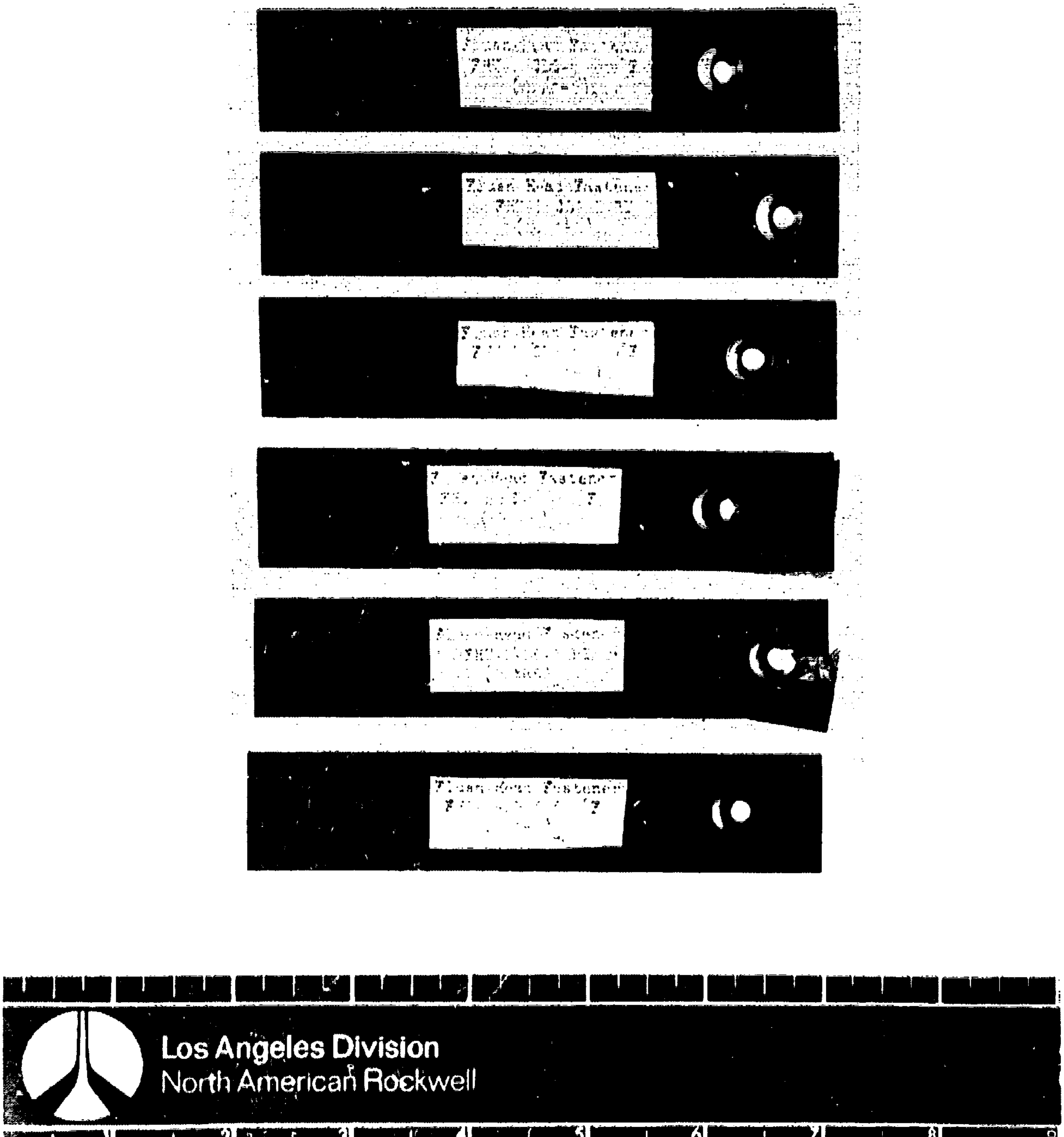


Figure 130. Typical Failed Flush Head Single Lap Graphite/Epoxy (Type AS/3002, Batch) to Steel Mechanical Joints - Countersunk Side Shown

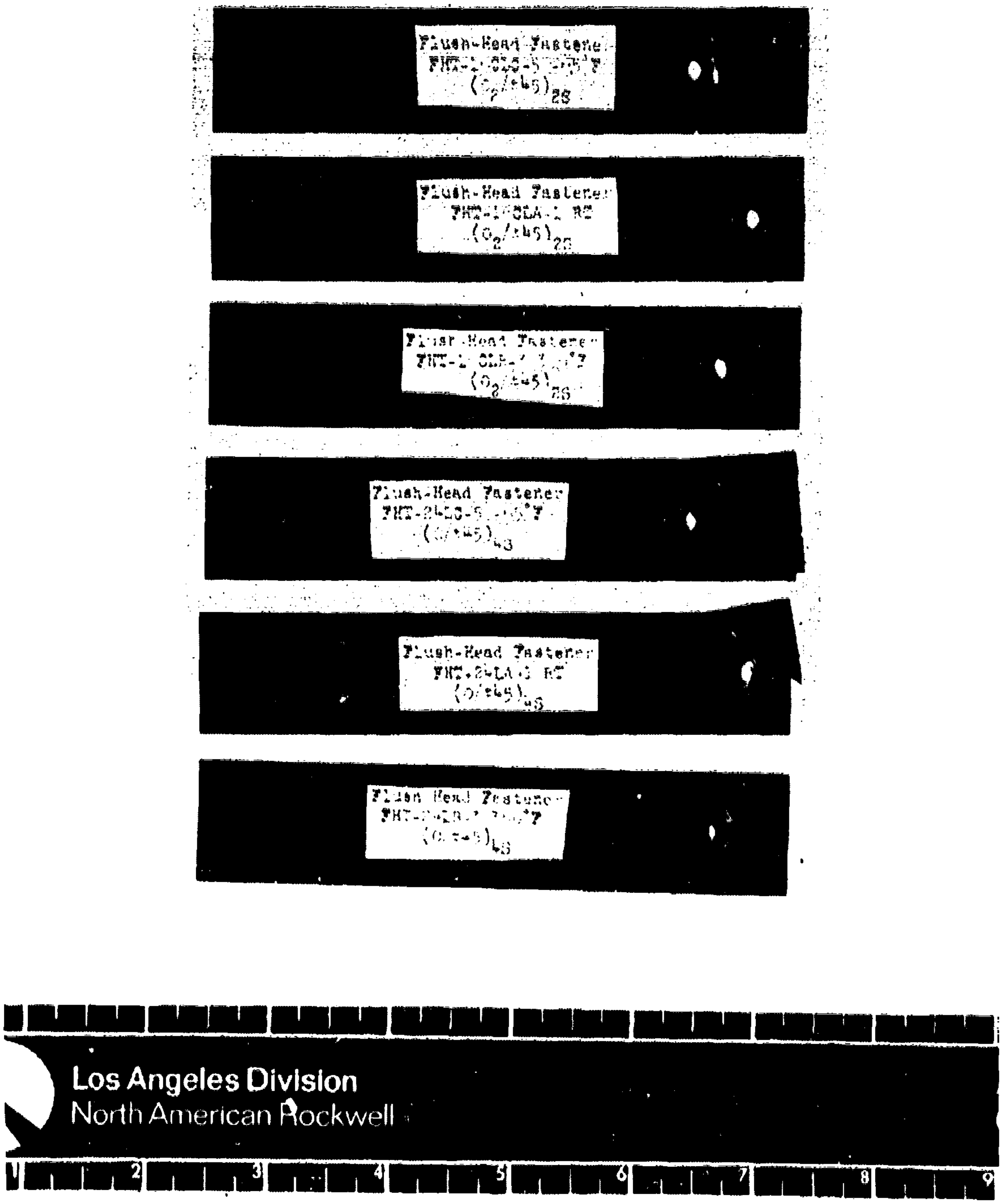


Figure 131. Typical Failed Flush Head Single Lap Graphite/Epoxy (Type AS/3002, Batch) to Steel Mechanical Joints - Countersunk Side Down

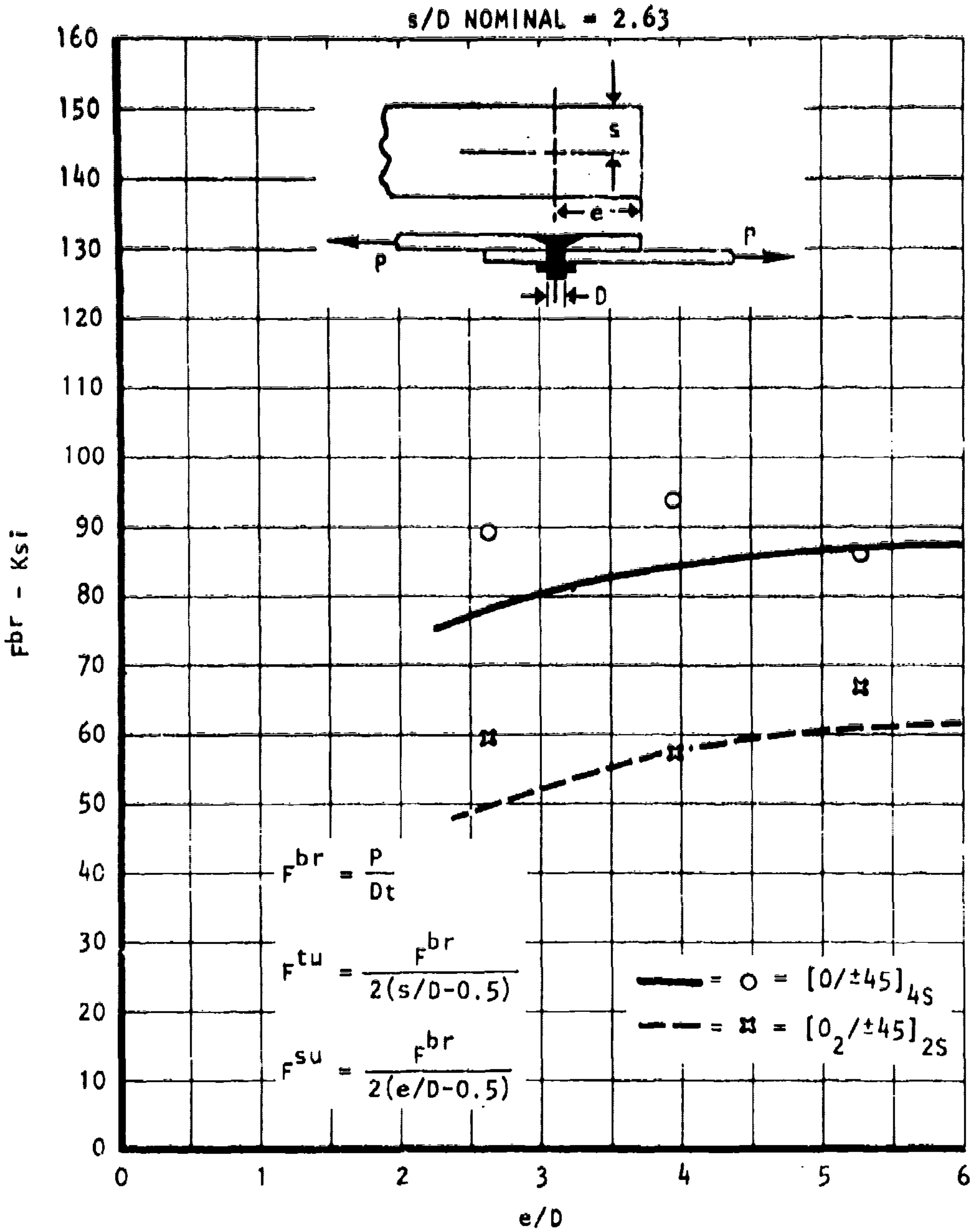


Figure 132. Graphite/Epoxy to Steel Mechanical Joint Single Lap Bearing Strength Versus e/D at -65°F (Type AS/3002, Batch) Flush Head Fastener

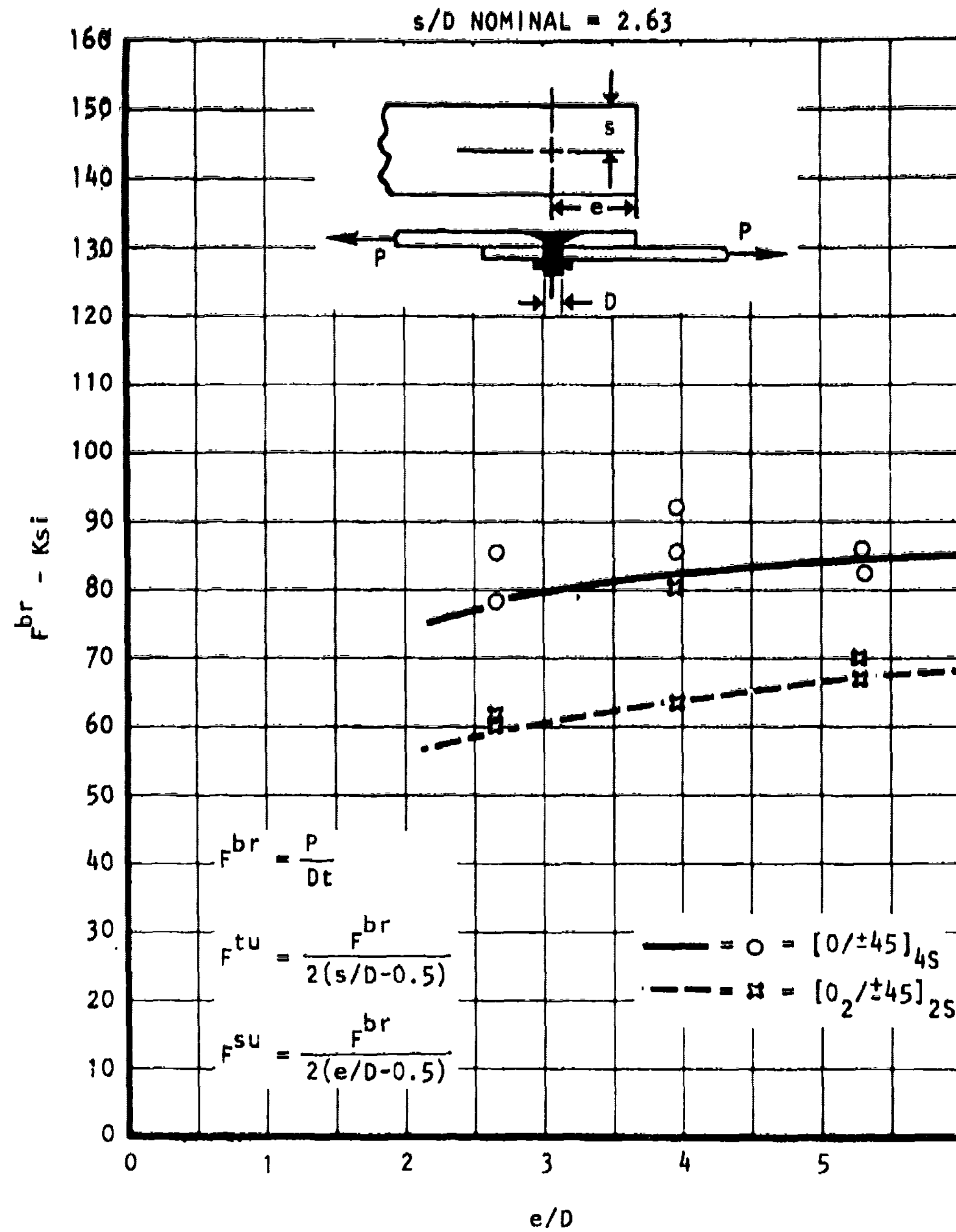


Figure 133. Graphite/Epoxy to Steel Mechanical Single Lap Bearing Strength versus e/D at Room Temperature (Type AS/3002, Batch) Flush Head Fastener

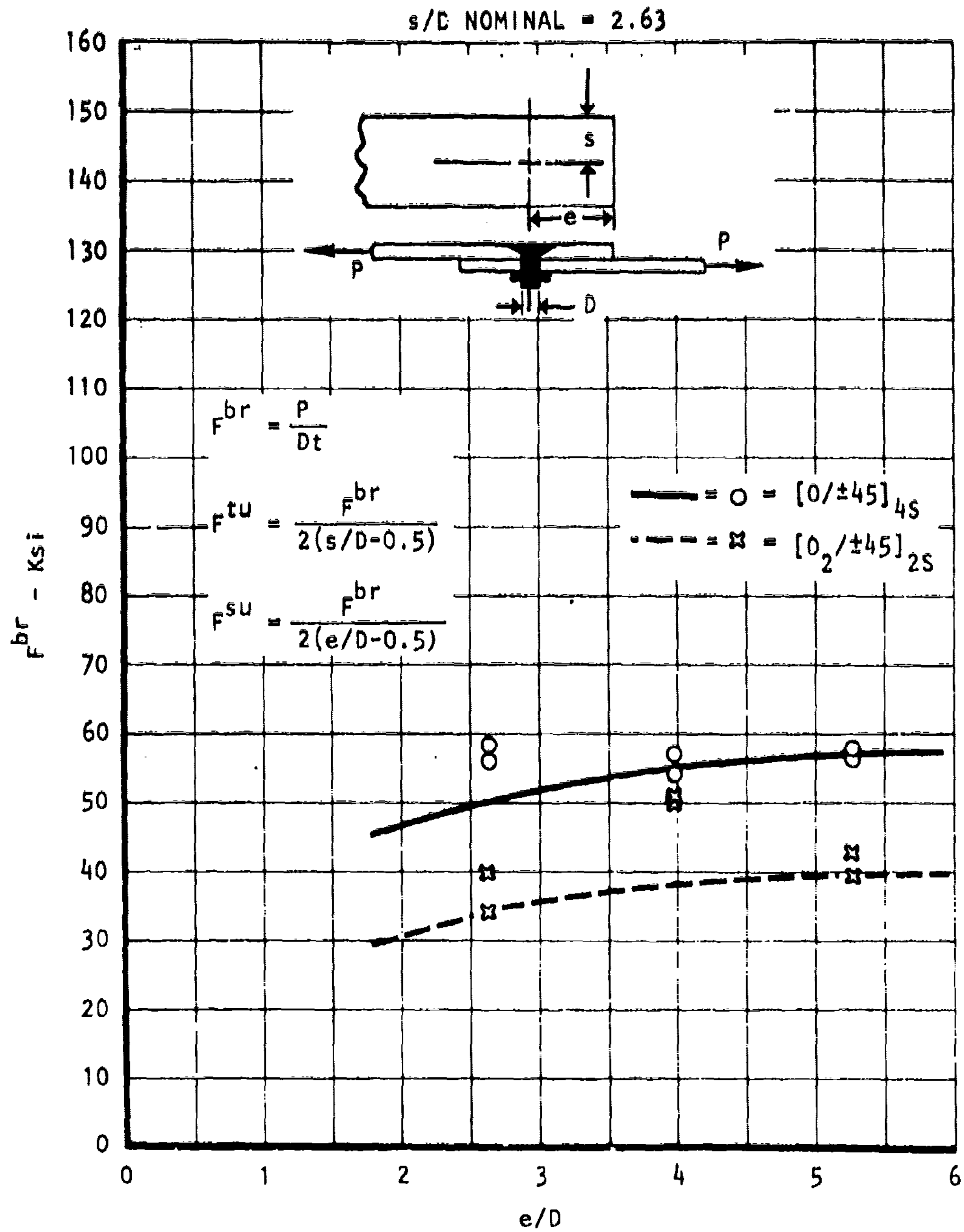


Figure 134. Graphite/Epoxy to Steel Mechanical Single Lap Bearing Strength Versus e/D at 350°F (Type AS/3002, Batch) Flush Head Fastener

Untreated Graphite/Epoxy (Type A/3002) to Steel

Table LI presents test data for single lap graphite/epoxy (Type A/3002 batch untreated) to steel tension-loaded flush head fastener mechanical joints. The laminate orientation used was $[0/\pm45/90]_{2S}$ with a nominal joint geometry s/D of 2.63 and e/D values of 2.63, 3.95, and 5.26. Three test temperatures were used: room temperature, 350°F, and -65°F. All failures were of the bearing type except the -65°F specimen with an e/D of 2.63, which failed in shearout. Figure 135 presents typical failed specimens of the bearing-type failure mode.

The bearing strengths appeared to be generally independent of the e/D range tested (2.63 to 5.26) (See figure 136.) Bearing strength, as expected, decreased as temperature increased as shown in figure 137.

Comparison of untreated graphite/epoxy flush joint strengths with average comparable protruding head fastener joint strengths show that flush-head joint strengths averaged 32 to 49 percent lower values. (Compare table LI with table LIV.) Similar trends were observed for the treated graphite/epoxy flush and protruding head mechanical joints.

Finally, when compared to the results obtained for the treated joints, the trend previously observed (increased bearing strength with decreasing percentages of 0° plies and increased percentages of ±45° plies) was again followed (i.e., the $[0/\pm45/90]_S$ untreated joints had higher bearing strengths than the $[0/\pm45]_S$ or $[0_2/\pm45]_S$ treated joints).

TABLE LI. GRAPHITE/EPOXY TO STEEL MECHANICAL FLUSH JOINT SINGLE LAP STATIC TENSION DATA - UNTREATED (TYPE A/3002, BATCH), FASTENER: NAS 1203*, $s/_D$ (NOMINAL) = 2.63. $[0/\pm45/90]_{2S}$

Specimen Number	Orientation	Temp (°F)	t (in.)	$\frac{e}{D}$	$\frac{D}{t}$	P Test (lb)	F^{br} (Ksi)	F^{tu} (Ksi)	F^{su} (Ksi)	Failure Mode ①
FHT-16LA1	$[0/\pm45/90]_{2S}$	70	0.096	2.63	1.98	1,605	88.0	20.6	20.6	B
FHT-16LA2	$[0/\pm45/90]_{2S}$	70	0.096	2.63	1.98	1,470	80.6	18.9	18.9	B
FHT-16LA3	$[0/\pm45/90]_{2S}$	350	0.096	2.63	1.98	925	50.7	11.9	11.9	B
FHT-16LA4	$[0/\pm45/90]_{2S}$	350	0.096	2.63	1.98	945	51.8	12.1	12.1	B
FHT-16LA5	$[0/\pm45/90]_{2S}$	-65	0.096	2.63	1.98	1,925	105.6	24.8	24.8	S
FHT-16LB1	$[0/\pm45/90]_{2S}$	70	0.096	3.95	1.98	1,645	90.2	21.2	13.1	B
FHT-16LB2	$[0/\pm45/90]_{2S}$	70	0.096	3.95	1.98	1,675	91.8	21.5	13.3	B
FHT-16LB3	$[0/\pm45/90]_{2S}$	350	0.096	3.95	1.98	730	40.0	9.39	5.81	B
FHT-16LB4	$[0/\pm45/90]_{2S}$	350	0.096	3.95	1.98	755	41.4	9.71	6.00	B
FHT-16LB5	$[0/\pm45/90]_{2S}$	-65	0.096	3.95	1.98	1,860	102.0	23.9	14.8	B
FHT-16LC1	$[0/\pm45/90]_{2S}$	70	0.096	5.26	1.98	1,655	90.7	21.3	9.52	B
FHT-16LC2	$[0/\pm45/90]_{2S}$	70	0.096	5.26	1.98	1,570	86.1	20.2	9.03	B
FHT-16LC3	$[0/\pm45/90]_{2S}$	350	0.096	5.26	1.98	795	43.6	10.2	4.58	B
FHT-16LC4	$[0/\pm45/90]_{2S}$	350	0.096	5.26	1.98	875	48.0	11.2	5.04	B
FHT-16LC5	$[0/\pm45/90]_{2S}$	-65	0.096	5.26	1.98	2,125	116.5	27.4	12.24	B

*160,000 to 180,000 psi heat-treat, flush-head fastener; diameter = 0.19 inch (nominal)

① B = bearing, T = net tension, S = shearout

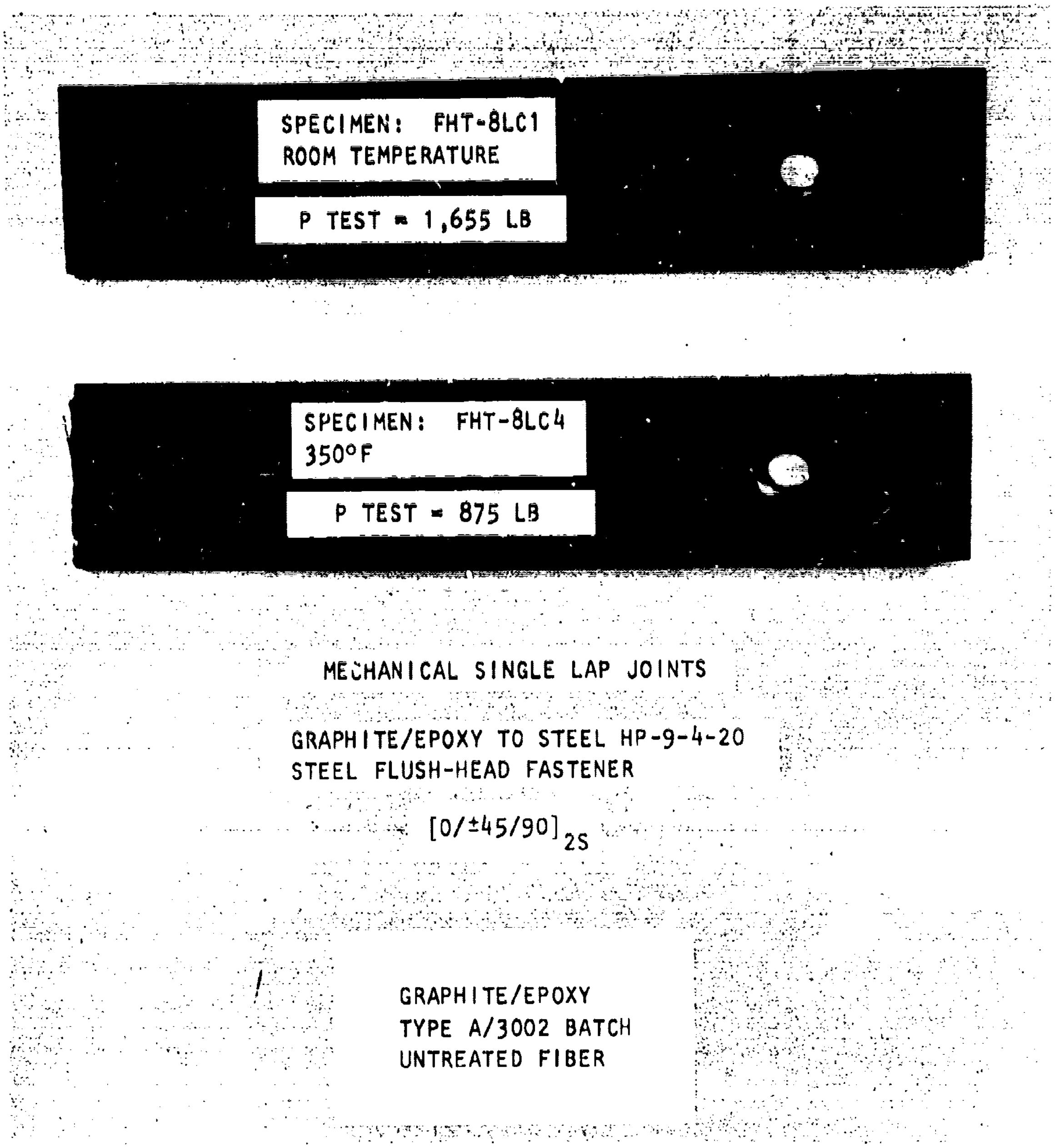


Figure 135. Typical Failed Single Lap Mechanical Joint Specimens - Flush Fastener - Graphite/Epoxy to Steel

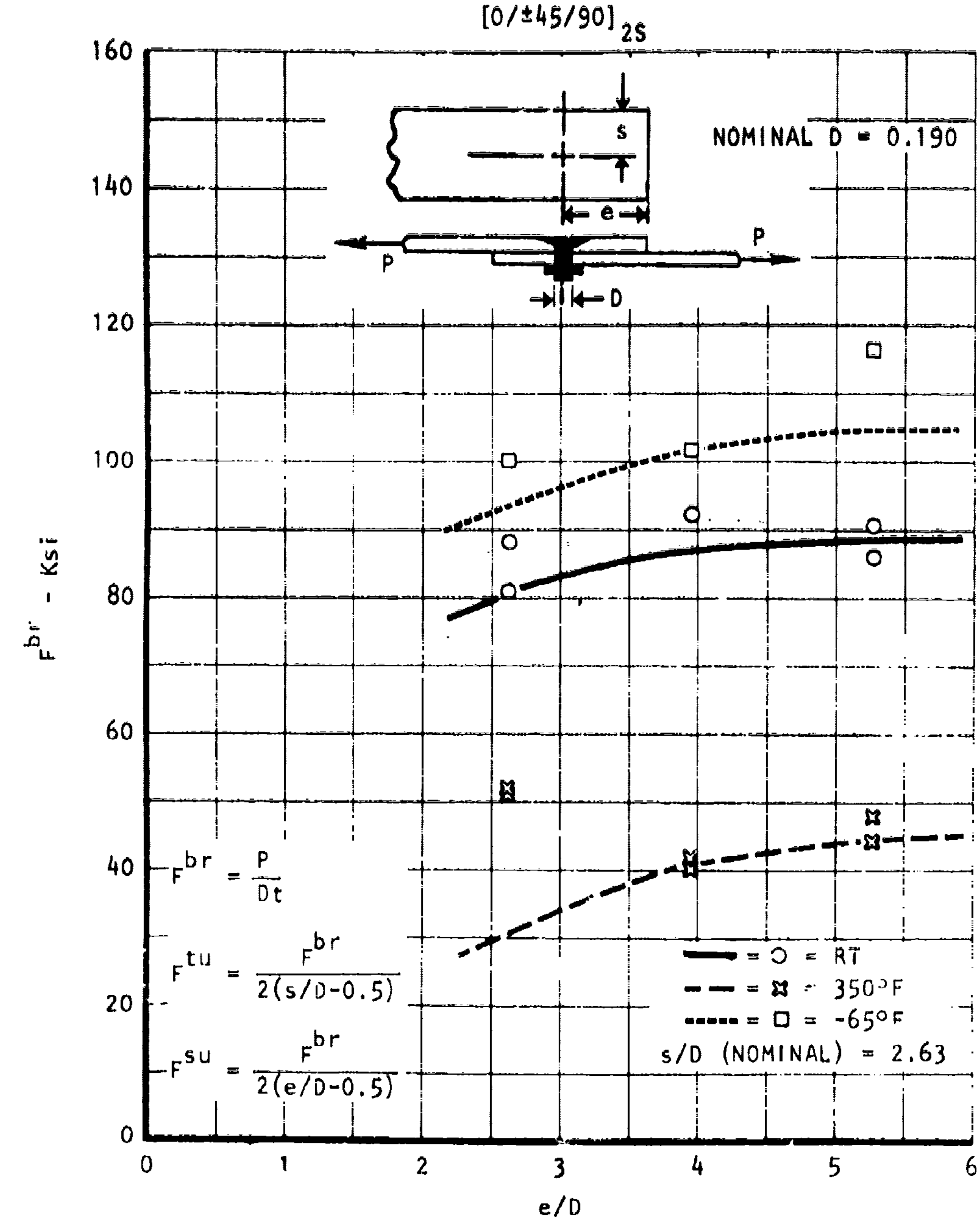


Figure 136. Graphite/Epoxy to Steel Mechanical Single Lap Bearing Strengths Versus e/D (Type A/3002, Batch) Flush Head Fasteners

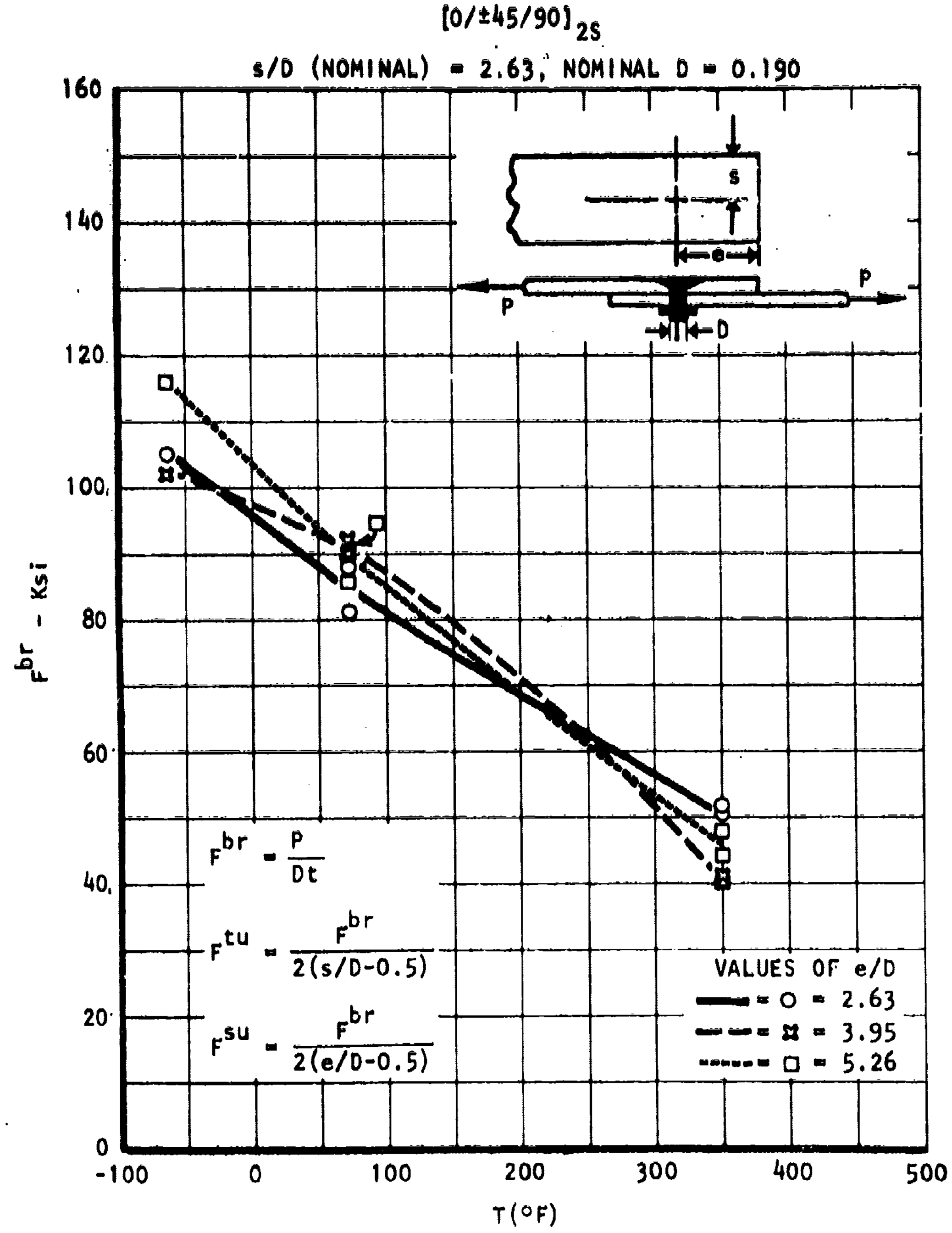


Figure 137. Flush Head Single Lap Mechanical Joint Bearing Strengths Versus Temperature (Graphite/Epoxy (Type A/3002, Batch) to Steel Joints)

Tension-Loaded Joint - Protruding-Head Fastener

Treated Graphite/Epoxy (Type AS/3002) to Steel

Tension data for Type AS/3002 batch (treated) $[0/\pm45]_S$ and $[0_2/\pm45]_S$ graphite/epoxy to steel single lap mechanical joints are presented in tables LII and LIII. NAS 1303 protruding-head fasteners were used for all tests (160 to 180 Ksi heat-treat). As in the case of the flush-head fastener tests, three temperatures (room temperature, -65°F, and 350°F) as well as three e/D ratios (nominal 2.63, 3.95, and 5.26) were used for each orientation tested. Furthermore, all tests also had an s/D ratio of 2.63. The typical failure mode for -65°F and room-temperature specimens was net tension or a combination of net tension and shearout, while all the 350°F specimens had bearing failures. (Refer to tables LII and LIII, and figure 138.)

Figures 139 through 141 present a plot of bearing strength versus e/D for the three test temperatures. The bearing strengths for -65°F and room temperature were found to increase with e/D, while the 350°F plot showed an almost constant bearing strength versus e/D. The reason for the variation of bearing strength is that the modes of failures for the -65°F and room temperature tests were net tension/shearout rather than bearing. The 350°F tests all exhibited bearing failures. The 350°F bearing strengths (average F^{br} = 70 Ksi) were also found to be about 45 percent lower than those at -65°F and room temperature (average F^{br} = 130 Ksi). Furthermore, as previously mentioned, the protruding-head joints were 25 to 59 percent stronger than the equivalent flush head single lap joints. (Refer to tables XLVIX, L, LII, and LIII.)

TABLE LII. GRAPHITE/EPOXY TO STEEL MECHANICAL JOINT SINGLE LAP STATIC TENSION DATA (TYPE AS/3002, BATCH). FASTENER: NAS 1303*, S/D (NOMINAL) = 2.63, $[0/\pm45]_S$

Specimen Number	Orientation	Temp (°F)	t (in.)	$\frac{e}{D}$	$\frac{D}{t}$	P Test (lb)	F^{br} (Ksi)	F^{tu} (Ksi)	F^{su} (Ksi)	Failure Mode ①
PHT-6LA1	$[0/\pm45]_S$	70	0.0370	2.63	5.14	848	120.63	28.32	28.32	T
PHT-6LA2	$[0/\pm45]_S$	70	0.0305	2.63	6.23	898	154.96	36.38	36.38	T, S
PHT-6LA3	$[0/\pm45]_S$	350	0.0365	2.63	5.21	616	88.83	20.85	20.85	B
PHT-6LA4	$[0/\pm45]_S$	350	0.0360	2.63	5.28	562	82.16	19.29	19.29	B
PHT-6LA5	$[0/\pm45]_S$	-65	0.0375	2.63	5.07	904	126.88	29.78	29.78	T
PHT-6LB1	$[0/\pm45]_S$	70	0.0372	3.95	5.11	1,086	153.65	36.07	22.27	T
PHT-6LB2	$[0/\pm45]_S$	70	0.0375	3.95	5.07	1,132	158.88	37.30	23.03	T
PHT-6LB3	$[0/\pm45]_S$	350	0.0370	3.95	5.14	545	77.53	18.20	11.24	B
PHT-6LB4	$[0/\pm45]_S$	350	0.0380	3.95	5.00	543	75.21	17.66	10.90	B
PHT-6LB5	$[0/\pm45]_S$	-65	0.0375	3.95	5.07	920	129.12	30.33	18.71	T
PHT-6LC1	$[0/\pm45]_S$	70	0.0370	5.26	5.14	1,112	158.18	37.13	16.62	T
PHT-6LC2	$[0/\pm45]_S$	70	0.0365	5.26	5.21	1,090	157.17	36.89	16.51	T
PHT-6LC3	$[0/\pm45]_S$	350	0.0375	5.26	5.07	506	71.02	16.67	7.46	B
PHT-6LC4	$[0/\pm45]_S$	350	0.0365	5.26	5.21	563	81.18	19.06	8.53	B
PHT-6LC5	$[0/\pm45]_S$	-65	0.0375	5.26	5.07	1,000	140.35	32.95	14.74	T

*160,000 to 180,000 psi heat-treat, protruding-head fastener; diameter = 0.19 inch (nominal)

① B = bearing, T = net tension, S = shearout

TABLE LIII. GRAPHITE/EPOXY TO STEEL MECHANICAL JOINT SINGLE LAP STATIC TENSION DATA (TYPE AS/3002, BATCH), FASTENER: NAS 1303*, $s/_D$ (NOMINAL) = 2.63, $[0_2/\pm45]_S$

Specimen Number	Orientation	Temp (°F)	t (in.)	$\frac{e}{D}$	$\frac{D}{t}$	P test (lb)	F^{br} (Ksi)	F^{tu} (Ksi)	F^{su} (Ksi)	Failure Mode (1)
PHT-8C-LA1	$[0_2/\pm45]_S$	70	0.0495	2.63	3.84	1,250	132.91	31.20	31.20	T,S
PHT-8C-LA2	$[0_2/\pm45]_S$	70	0.0510	2.63	3.73	1,266	130.65	30.67	30.67	T,S
PHT-8C-LA3	$[0_2/\pm45]_S$	350	0.0495	2.63	3.84	680	72.30	16.97	16.97	B
PHT-8C-LA4	$[0_2/\pm45]_S$	350	0.0485	2.63	3.92	547	59.36	13.93	13.93	B
PHT-8C-LA5	$[0_2/\pm45]_S$	-65	0.0495	2.63	3.84	904	96.12	22.56	22.56	T
PHT-8C-LB1	$[0_2/\pm45]_S$	70	0.0483	3.95	3.93	1,464	159.53	37.45	23.12	S,T
PHT-8C-LB2	$[0_2/\pm45]_S$	70	0.0500	3.95	3.80	1,426	150.11	35.24	21.76	S,T
PHT-8C-LB3	$[0_2/\pm45]_S$	350	0.0510	3.95	3.73	722	74.51	17.49	10.80	B
PHT-8C-LB4	$[0_2/\pm45]_S$	350	0.0485	3.95	3.92	685	74.34	17.45	10.77	B
PHT-8C-LB5	$[0_2/\pm45]_S$	-65	0.0485	3.95	3.92	1,276	138.47	32.51	20.07	T
PHT-8C-LC1	$[0_2/\pm45]_S$	70	0.0497	5.26	3.82	1,596	169.01	39.67	17.75	T,S
PHT-8C-LC2	$[0_2/\pm45]_S$	70	0.0492	5.26	3.86	1,500	160.46	37.67	16.86	T,S
PHT-8C-LC3	$[0_2/\pm45]_S$	350	0.0490	5.26	3.88	648	69.60	16.34	7.31	B
PHT-8C-LC4	$[0_2/\pm45]_S$	350	0.0495	5.26	3.84	636	67.62	15.87	7.10	B
PHT-8C-LC5	$[0_2/\pm45]_S$	-65	0.0465	5.26	4.09	1,326	150.09	35.23	15.77	T,S

*160,000 to 180,000 psi heat-treat, protruding head-fastener; diameter = 0.19 inch (nominal)

(1) B = bearing, T = net tension, S = shear out

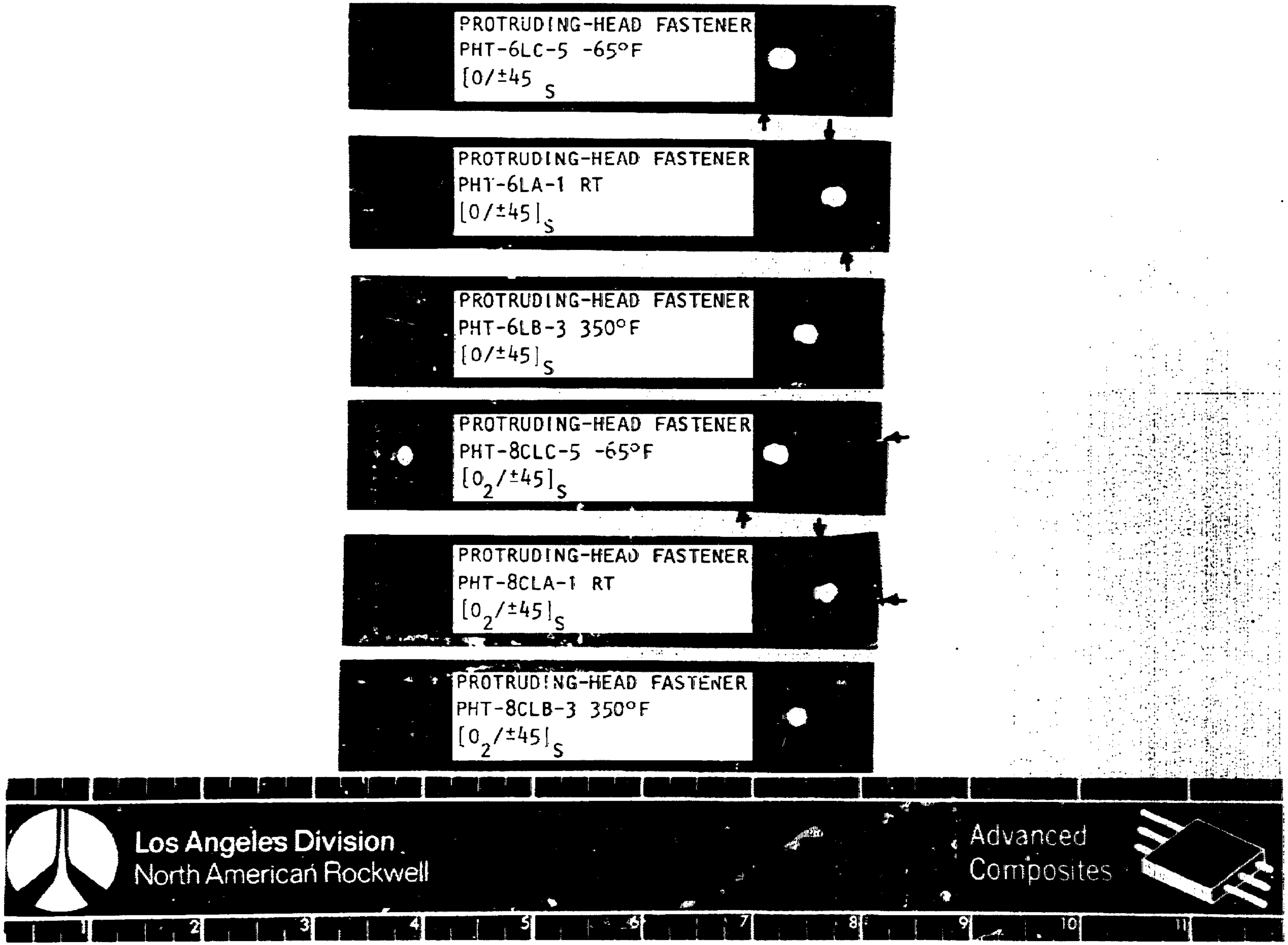


Figure 138. Typical Failed Protruding Head Single Lap Graphite/Epoxy (Type AS/3002, Batch) to Steel Mechanical Joints

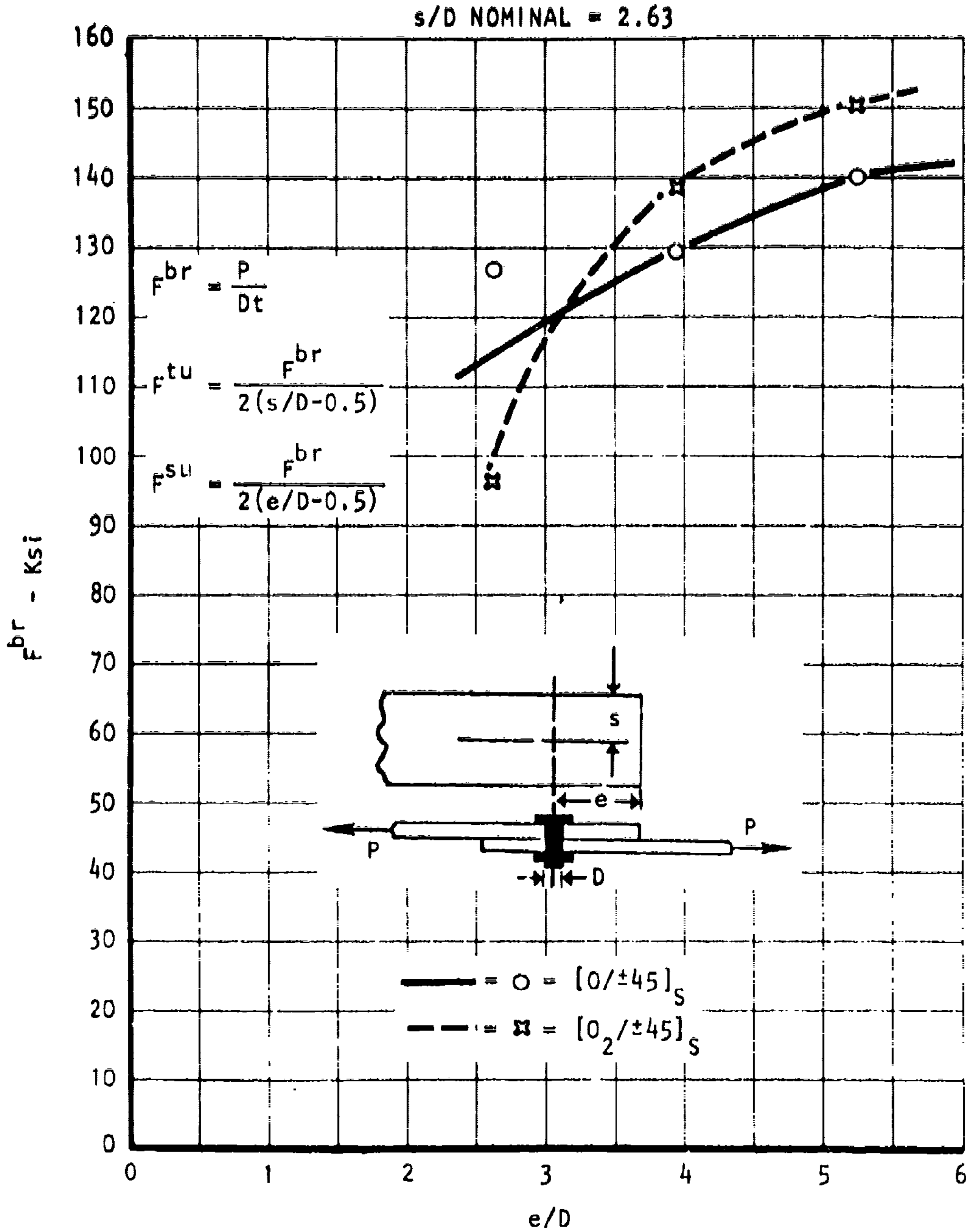


Figure 139. Graphite/Epoxy to Steel Mechanical Joint Single Lap Bearing Strength Versus e/D at -65°F (Type AS/3002, Batch) Protruding Head Fastener

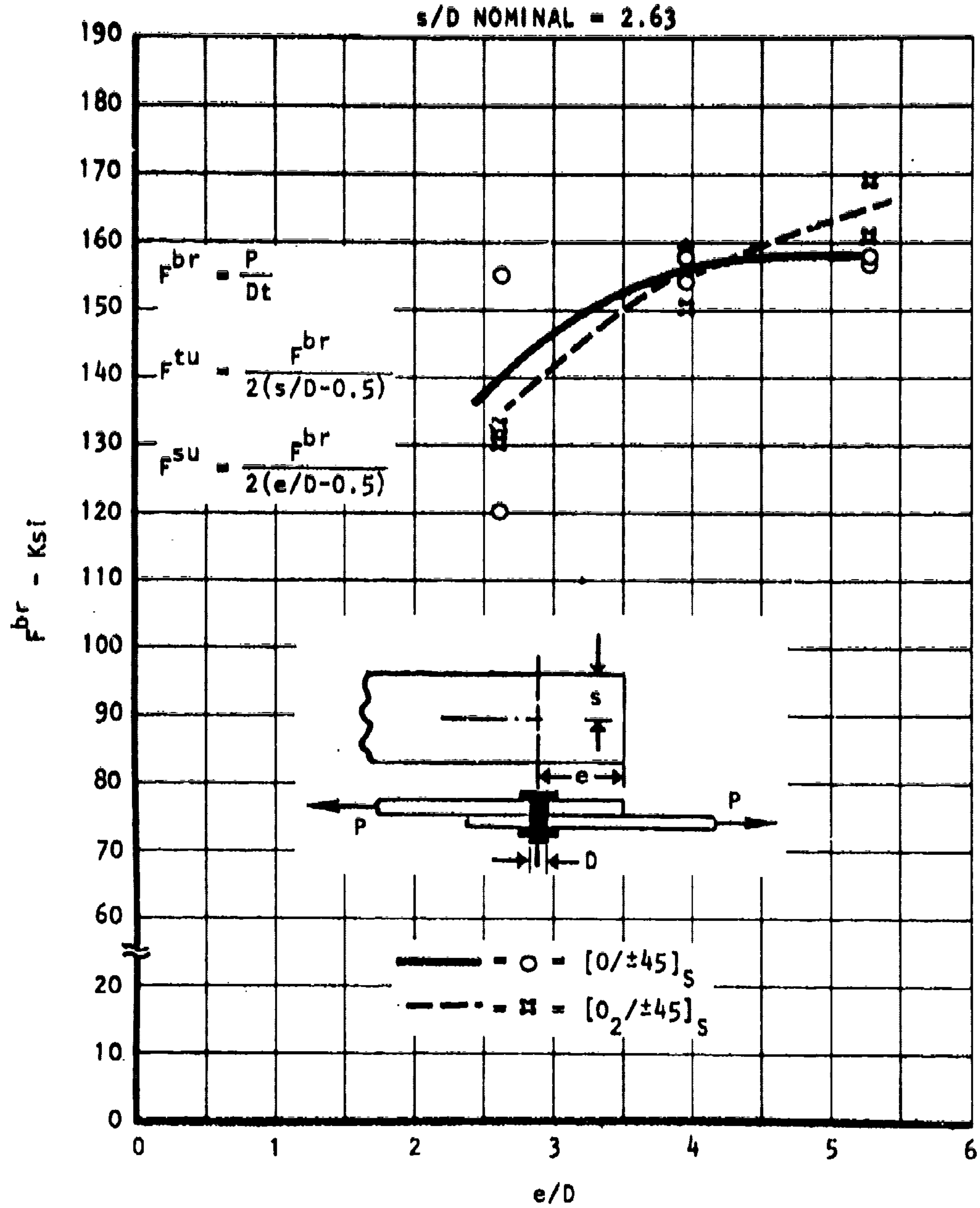


Figure 140. Graphite/Epoxy to Steel Mechanical Joint Single Lap Bearing Strength Versus e/D at Room Temperature (Type AS/3002, Batch) Protruding Head Fastener

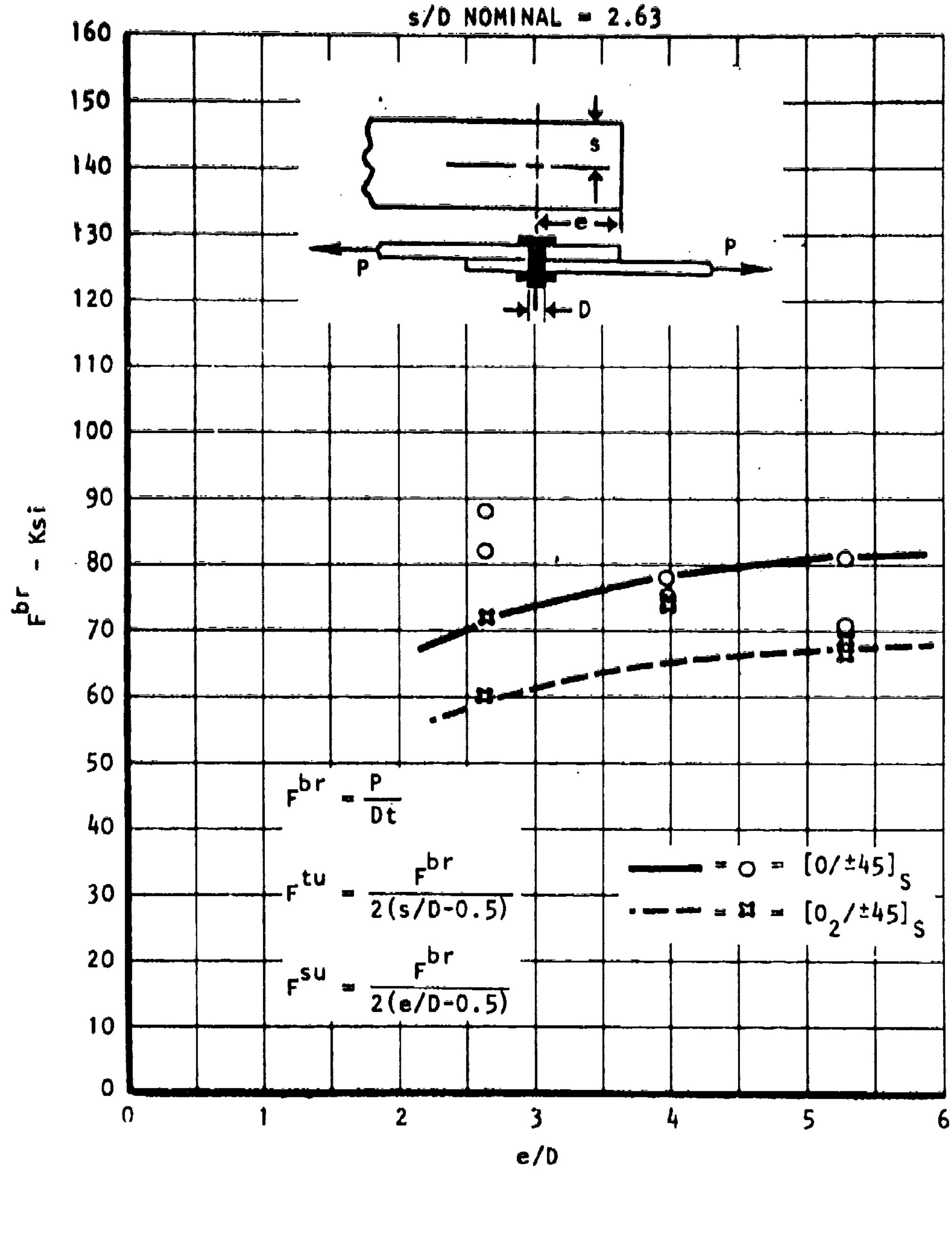


Figure 141. Graphite/Epoxy to Steel Mechanical Joint Single Lap Bearing Strength Versus e/D at 350°F (Type AS/3002, Batch) Protruding Head Fastener

Untreated Graphite/Epoxy (Type A/3002) to Steel

Table LIV presents test data for tension-loaded protruding head fastener mechanical joints of graphite/epoxy (Type A/3002, batch untreated fiber) to steel single lap configurations. Figure 142 shows typical failed specimens with bearing-type failure mode, which was characteristic of all the $[0/\pm45/90]_S$ orientation and e/D tested. Figure 143 presents the bearing strength data versus the e/D ratio range (2.63, 3.95, and 5.26) tested.

The figure shows that the bearing strength is generally independent of e/D range tested for the [0/±45/90] orientation. Figure 144 shows the same data plotted as a function of test temperature, which shows that, as expected, bearing strengths decrease as temperature increases; 350°F values averaged about 53 percent of room temperature values.

TABLE LIV. GRAPHITE/EPOXY TO STEEL MECHANICAL JOINT SINGLE LAP STATIC TENSION DATA - UNTREATED (TYPE A/3002, BATCH), FASTENER: NAS 1303*, $^S/_D$ (NOMINAL) = 2.63, $[0/\pm45/90]_S$

Specimen Number	Orientation	Temp (°F)	t (in.)	$\frac{e}{D}$	$\frac{D}{t}$	P Test (lb)	F^{br} (Ksi)	F^{tu} (Ksi)	F^{su} (Ksi)	Failure Mode (1)
PHT-8LA1	$[0/\pm45/90]_S$	70	0.048	2.63	3.96	1,260	138.1	32.4	32.4	B
PHT-8LA2	$[0/\pm45/90]_S$	70	0.048	2.63	3.96	1,550	169.9	39.9	39.9	B
PHT-8LA3	$[0/\pm45/90]_S$	350	0.048	2.63	3.96	683	74.9	17.6	17.6	B
PHT-8LA4	$[0/\pm45/90]_S$	350	0.048	2.63	3.96	785	86.1	20.2	20.2	B
PHT-8LA5	$[0/\pm45/90]_S$	-65	0.048	2.63	3.96	1,655	181.5	42.6	42.6	S
PHT-8LB1	$[0/\pm45/90]_S$	70	0.048	3.95	3.96	1,540	168.9	39.6	24.5	B
PHT-8LB2	$[0/\pm45/90]_S$	70	0.048	3.95	3.96	1,375	150.8	35.4	21.9	B
PHT-8LB3	$[0/\pm45/90]_S$	350	0.048	3.95	3.96	820	89.9	21.1	13.0	B
PHT-8LB4	$[0/\pm45/90]_S$	350	0.048	3.95	3.96	630	69.1	16.2	10.0	B
PHT-8LB5	$[0/\pm45/90]_S$	-65	0.048	3.95	3.96	1,635	179.3	42.1	26.0	B
PHT-8LC1	$[0/\pm45/90]_S$	70	0.048	5.26	3.96	1,330	145.8	34.2	15.3	B
PHT-8LC2	$[0/\pm45/90]_S$	70	0.048	5.26	3.96	1,380	151.3	35.5	15.9	B
PHT-8LC3	$[0/\pm45/90]_S$	350	0.048	5.26	3.96	830	91.0	21.3	9.55	B
PHT-8LC4	$[0/\pm45/90]_S$	350	0.048	5.26	3.96	735	80.6	18.9	8.46	B
PHT-8LC5	$[0/\pm45/90]_S$	-65	0.048	5.26	3.96	1,560	171.1	40.2	18.0	B

*160,000 to 180,000 psi heat-treat, protruding-head fastener; diameter = 0.19 inch (nominal)

(1) B = bearing, T = net tension, S = shearout

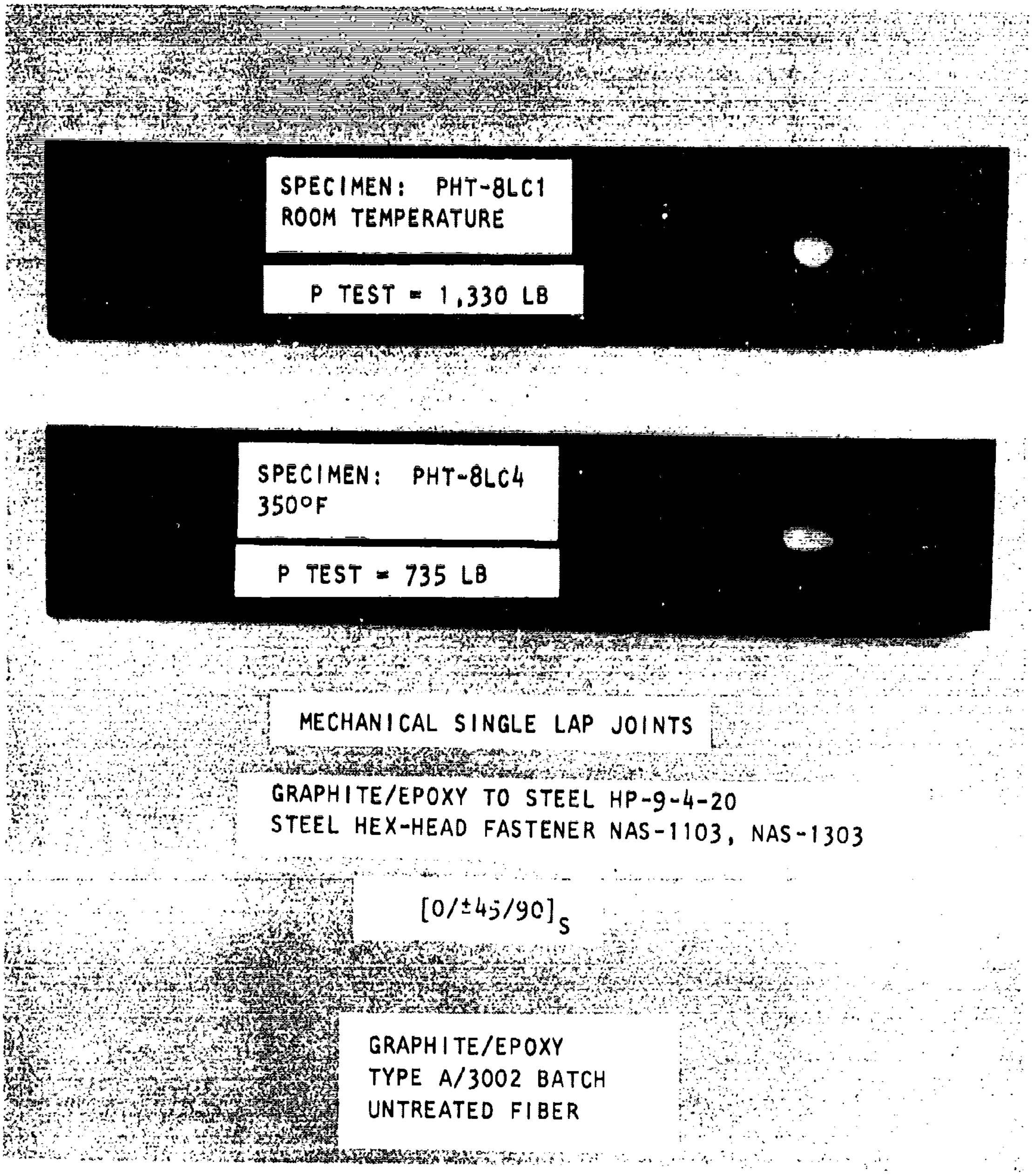


Figure 142. Typical Failed Single Lap Mechanical Joint Specimens - Hex Head Fastener - Graphite/Epoxy to Steel

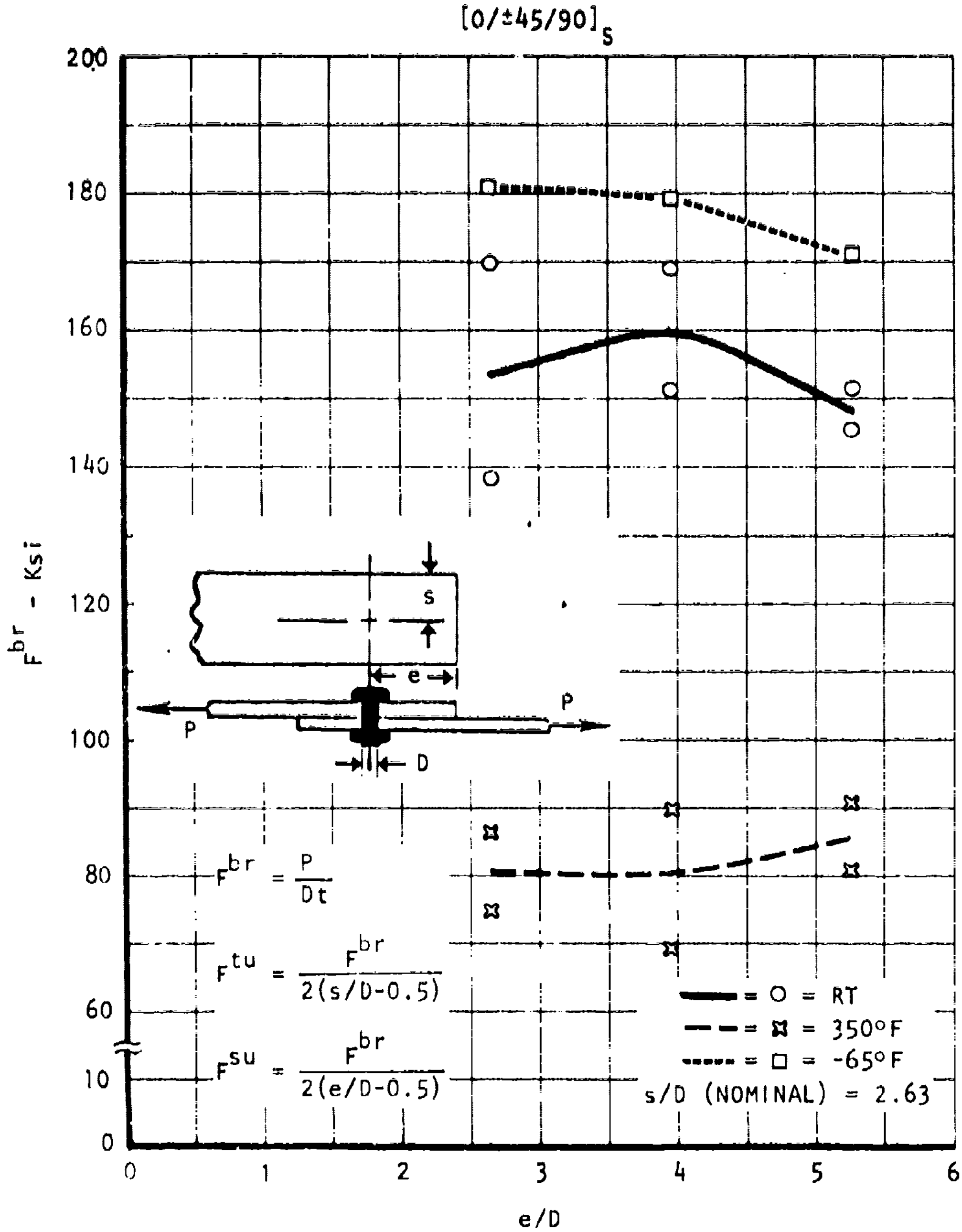


Figure 143. Graphite/Epoxy to Steel Mechanical Joint Single Lap Bearing Strengths Versus e/D (Type A/3002, Batch) Protruding Head Fasteners

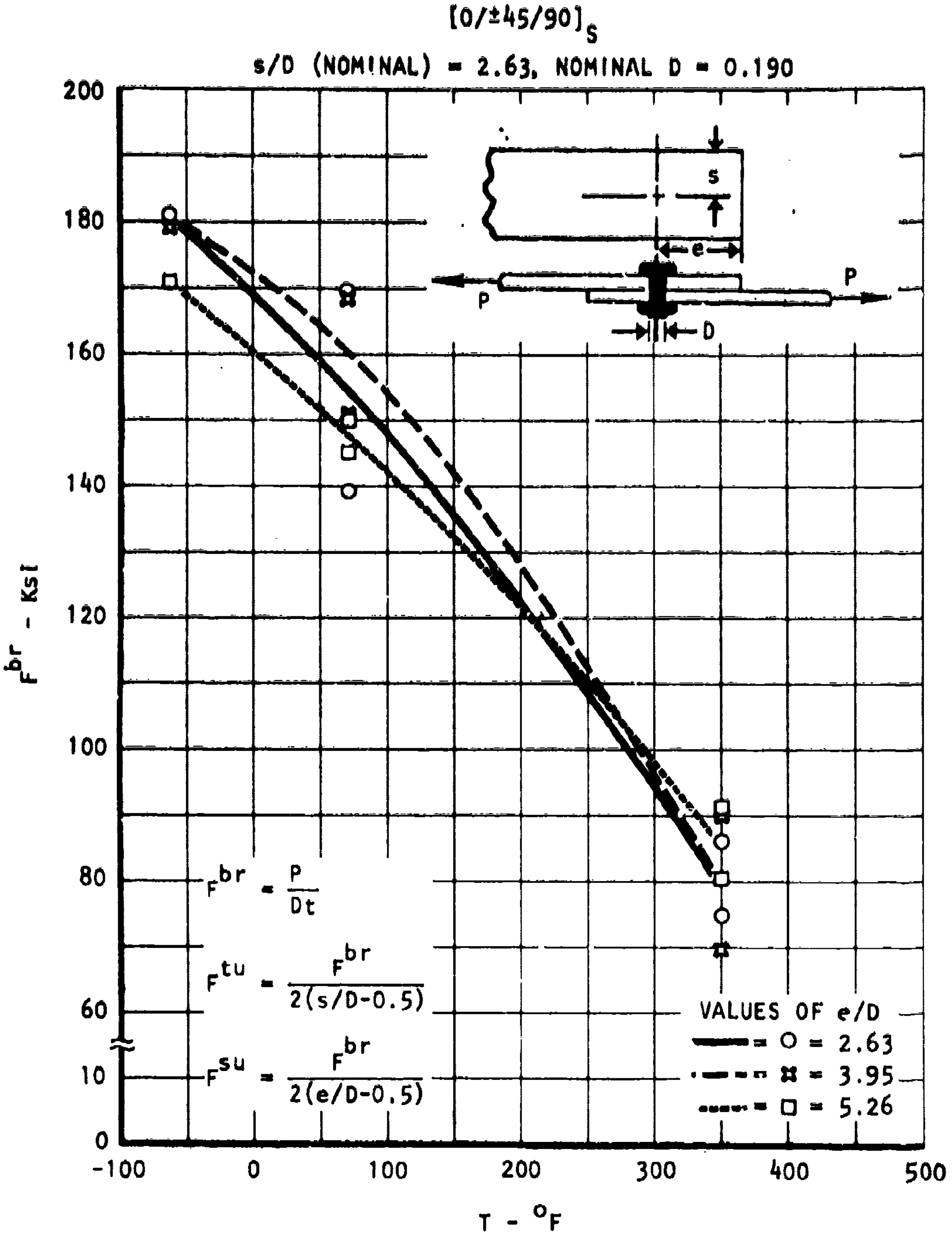


Figure 144. Protruding Head Single Lap Mechanical Joint Bearing Strengths Versus Temperature (Graphite/Epoxy (Type A/3002, Batch) to Steel Joints)

Compression-Loaded Joint - Flush-Head Fasteners

Treated Graphite/Epoxy (Type AS/3002) to Aluminum

Table LV presents compression data from flush-head fastener graphite/epoxy to aluminum mechanical joint specimens as shown in figure 145. NAS 1203 flush-head fasteners were used for all the tests (160 to 180 Ksi heat-treat). A nominal e/D of 3.42 was also maintained for all specimens, as well as nominal s/D of 2, 3.3, and 5. (Refer to table LV for exact s/D values.) Only room-temperature tests were run for the three orientations tested ($[0/\pm45]_{4S}$, $[0/\pm45/90]_{2S}$, and $[0_2/\pm45]_{2S}$), and all failures were a combination of bearing and secondary fastener failure. Typical failed specimens are shown in Figure 146.

The data are plotted in figure 147 as bearing strength versus fastener-spacing-to-fastener-diameter ratio. The plot shows that bearing strength remains fairly constant (less than 10 percent variation) with increasing s/D values. The average bearing strengths obtained ranged from 100 Ksi to 130 Ksi.

TABLE LV. GRAPHITE/EPOXY TO STEEL FLUSH-HEAD MECHANICAL JOINT ROOM-TEMPERATURE COMPRESSION DATA (TYPE AS/3002, BATCH), FASTENER: NAS 1203*, c/D (NOMINAL) = 3.42

Specimen Number	Orientation	t (in.)	Specimen Width w (in.)	s	$\frac{s}{D}$	$\frac{D}{t}$	P test (lb)	F^{br} (Ksi)	Failure Mode ①
FHC-24LA-1	$[0/\pm45]_{4S}$	0.1496	1.983	0.378	1.99	1.27	10,920	96.05	B,F
FHC-24LB-1	$[0/\pm45]_{4S}$	0.1477	2.990	0.678	3.57	1.29	11,850	105.57	B,F
FHC-24LC-1	$[0/\pm45]_{4S}$	0.1426	3.990	0.893	4.70	1.33	10,800	99.65	B,F
FHC-16LA-1	$[0/\pm45/90]_{2S}$	0.9030	1.985	0.390	2.05	2.04	8,730	123.51	B,F
FHC-16LB-1	$[0/\pm45/90]_{2S}$	0.0903	2.965	0.648	3.41	2.10	8,930	130.12	B,F
FHC-16LC-1	$[0/+45/90]_{2S}$	0.0966	3.982	0.895	4.71	1.97	8,835	120.34	B,F
FHC-16CLA-1	$[0_2/\pm45]_{2S}$	0.0923	1.985	0.398	2.10	2.06	7,880	112.33	B,F
FHC-16CLB-1	$[0_2/\pm45]_{2S}$	0.1002	2.972	0.632	3.33	1.90	9,480	124.49	B,F
FHC-16CLC-1	$[0_2/\pm45]_{2S}$	0.0962	3.967	0.9002	4.74	1.98	8,720	119.27	B,F

*160,000 to 180,000 psi heat-treat; flush-head fastener; diameter = 0.19 inch (nominal)

① B = bearing to laminate; F = secondary fastener failure

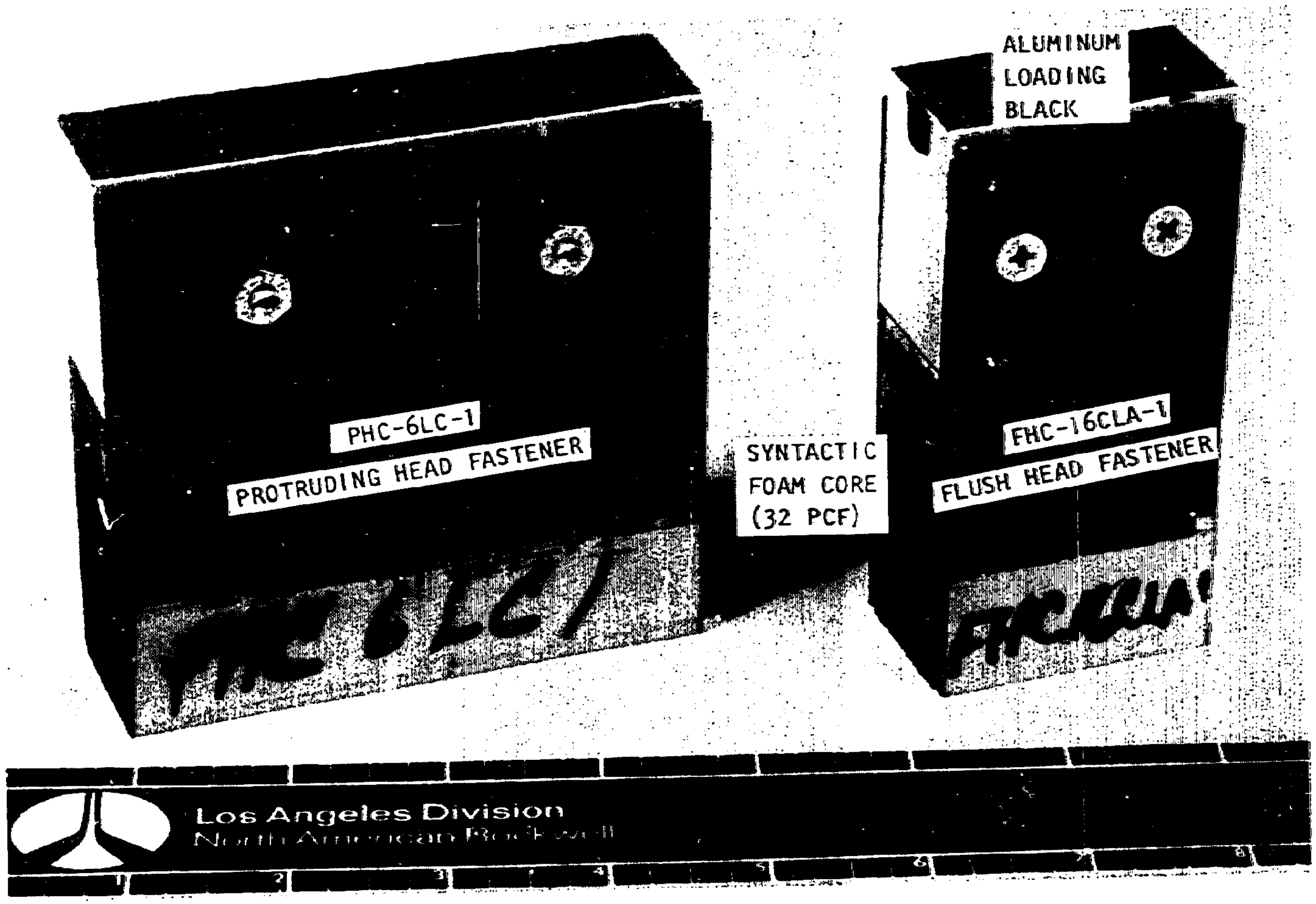


Figure 145. Compression Graphite/Epoxy Mechanical Joint Test Specimen Setup (Protruding Head and Flush Head Fasteners)

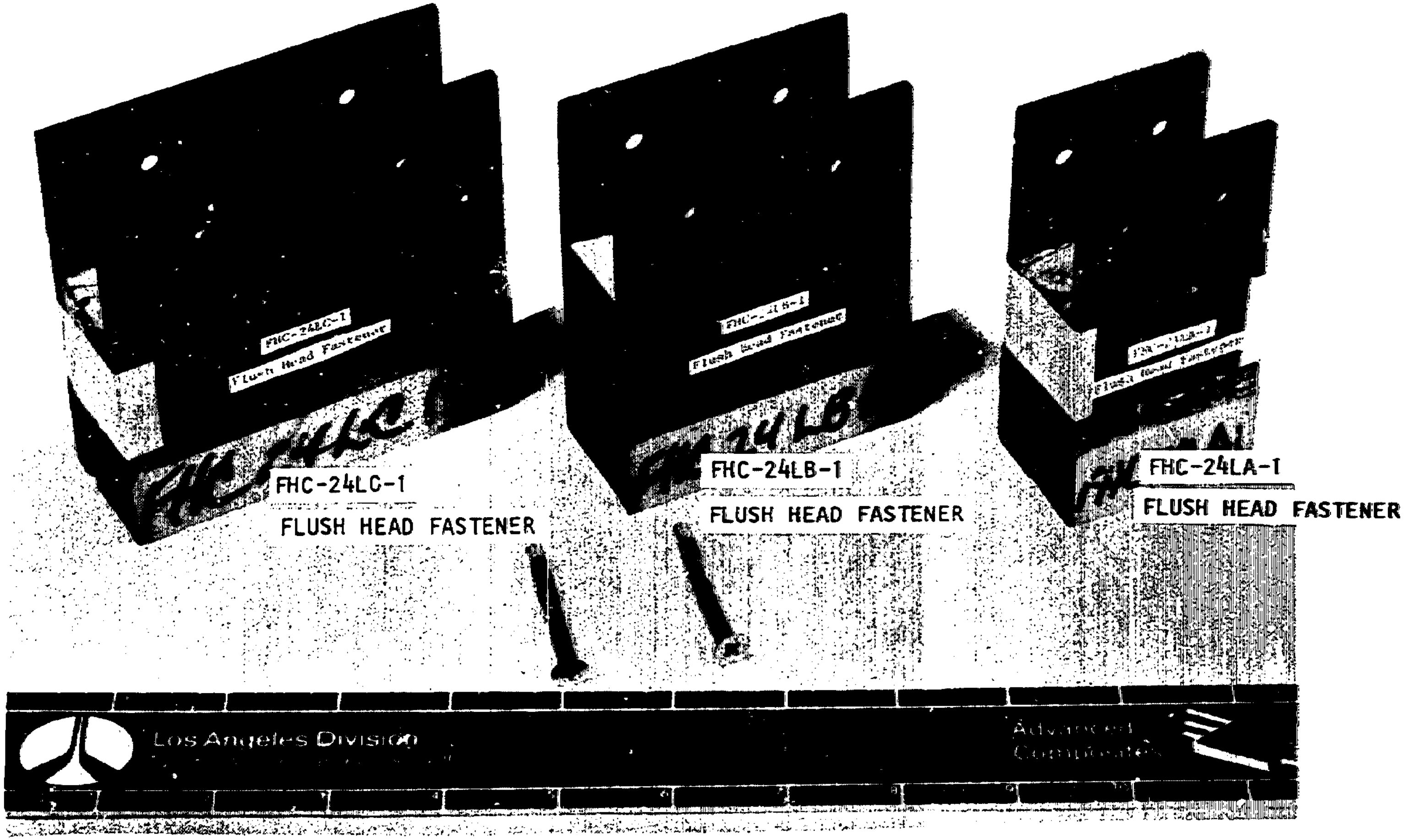


Figure 146. Typical Failed Graphite/Epoxy Compression Mechanical Joint Specimens (Flush Head Fasteners)

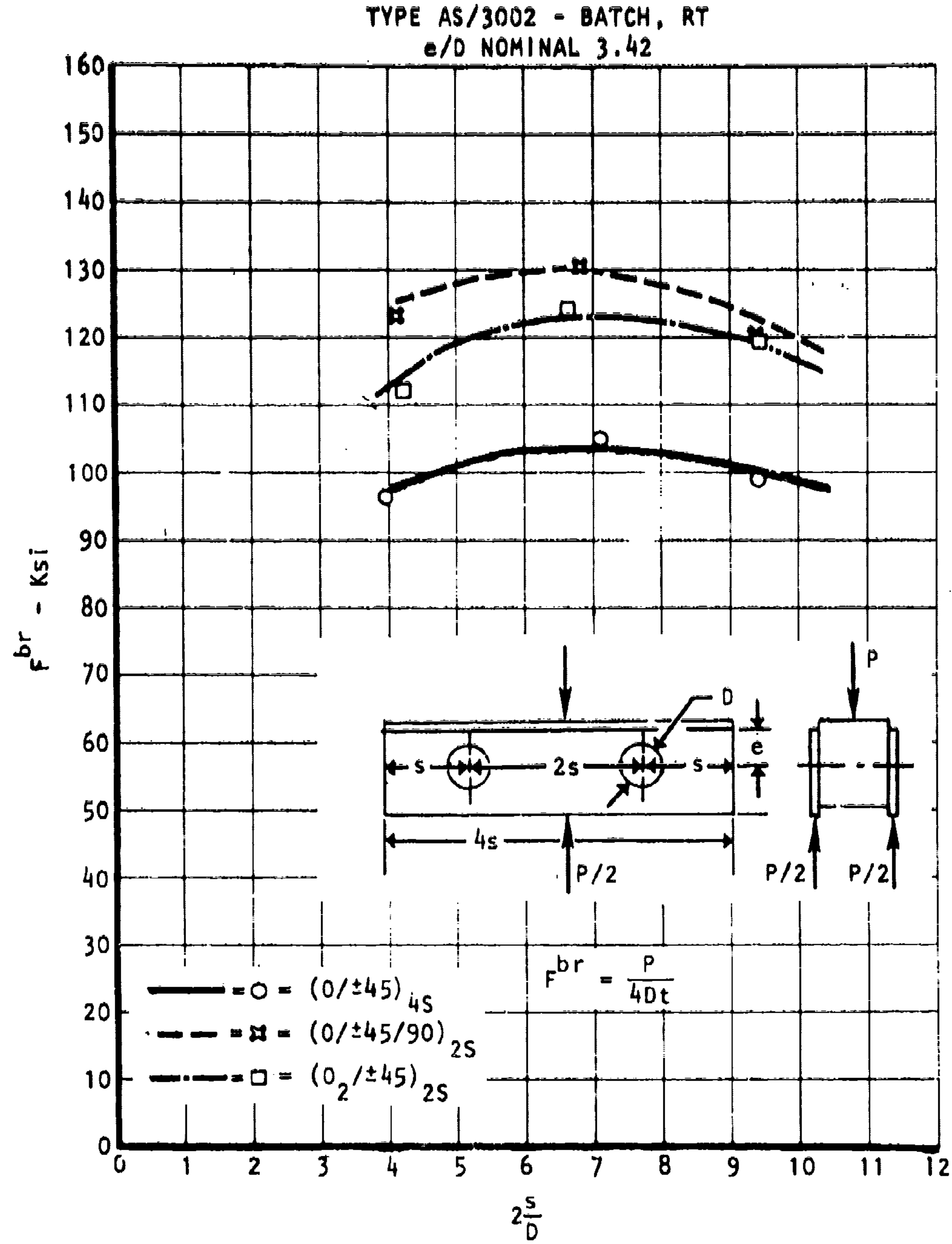


Figure 147. Bearing Strength Versus Fastener Spacing to Fastener Diameter Ratio for Flush Head Fastener Graphite/Epoxy to Aluminum Single Lap Mechanical Joints - Room Temperature

Compression-Loaded Joint - Protruding Head Fasteners

Treated Graphite/Epoxy (Type AS/3002) to Aluminum

Compression test data for room-temperature protruding head fastener graphite/epoxy to aluminum mechanical joint specimens are presented in table LVI. The test specimen configuration is shown in figure 145. As in the case of the flush-head fastener compression joint specimens, three orientations ($[0/\pm45]_S$, $[0/\pm45/90]_S$, and $[0_2/\pm45]_S$) and three s/D ratios (nominal 2, 3.3, and 5) were tested. The nominal e/D ratio for all the specimens was 3.42 as in the flush-head fastener case also. All failures were of the bearing type, although data for specimens PHC-6LB-1, PHC-6LC-1, and PHC-8LA-1 were disregarded because the test values were excessively high from bearing of the aluminum loading block directly on the syntactic foam core rather than fastener-to-laminate bearing. Typical failed specimens are shown in figure 148.

The data are also plotted in figure 149, and as was the case for the flush mechanical joint data, the bearing strength was constant for a given laminate regardless of s/D value (for the range tested. The flush-head fastener bearing strengths for compression ranged from 1 to 23 percent less than the values for the comparable protruding head fastener specimens. (See figures 147 and 149.)

Comparison of Tension-Loaded and Compression-Loaded Bearing Strengths

Average room-temperature bearing strengths of flush and protruding head fastened tension and compression-loaded joints are summarized for the three laminate orientations investigated.

Orientation	Fastener	Tension Loaded/Compression Loaded
$[0/\pm45]$	Flush Protruding	84.2/100.4 = 0.84 150.6/124.5 = 1.21
$[0_2/\pm45]$	Flush Protruding	67.3/118.7 = 0.57 150.4/142.1 = 1.06
$[0/\pm45/90]$	Flush Protruding	87.9/124.6 = 0.71 154.2/133.1 = 1.16

The flush head mechanical joints loaded in tension generally had lower bearing strengths than the comparable joints loaded in compression, while the opposite effect was noted for the protruding head joints. However, it should be noted that the compression-loaded flush-head mechanical joint actually consisted of a flush-head joint on only one face sheet of the sandwich, while the other face sheet could be construed as an equivalent protruding-head type joint. (See figure 146.) For flush-head design values, the tension-loaded values are recommended. For protruding-head design values, the valid compression loaded data offer the more conservative values.

TABLE LVI. GRAPHITE/EPOXY TO STEEL PROTRUDING-HEAD MECHANICAL JOINT ROOM TEMPERATURE COMPRESSION DATA (TYPE AS/3002, BATCH), FASTENER: NAS 1303*, $e/_D$ (NOMINAL) = 3.42

Specimen Number	Orientation	t (in.)	Specimen Width W (in.)	s	$\frac{s}{D}$	$\frac{D}{t}$	P Test (lb)	p^{br} (Ksi)	Failure Mode (1)	
PHC-6LA-1	$[0/\pm45]_S$	0.0371	1.910	0.345	1.82	5.12	3,510 (2)	124.49	B	
PHC-6LB-1	$[0/\pm45]_S$	0.0357	2.987	0.654	3.44	5.32	9.775	360.28	B	**
PHC-6LC-1	$[0/\pm45]_S$	0.0350	4.005	0.894	4.71	5.43	9,220	346.62	B	**
PHC-8LA-1	$[0/\pm45/90]_S$	0.0438	1.927	0.332	1.75	4.34	6,290	188.96	B	**
PHC-8LB-]	$[0/\pm45/90]_S$	0.0436	2.983	0.664	3.50	4.36	4,345	131.13	B	
PHC-8LC-1	$[0/\pm45/90]_S$	0.0450	4.012	0.902	4.75	4.22	4,260	135.09	B	
PHC-8CLA-1	$[0_2/\pm45]_S$	0.0475	1.940	0.370	1.95	4.00	4,890	135.46	B	
PHC-8CLB-1	$[0_2/\pm45]_S$	0.0466	3.027	0.633	3.33	4.08	5,640	159.25	B	
PHC-8CLC-1	$[0_2/\pm45]_S$	0.0488	4.005	0.910	4.79	3.89	4,880	131.58	B	

*160,000 to 180,000 psi heat-treat, protruding-head fastener; diameter = 0.19 inch (nominal)

(1) B = bearing to laminate; F = secondary fastener failure

(2) No edge supports used

**Invalid test value due to bearing of aluminum loading block on syntactic foam core rather than fastener-to-laminate bearing

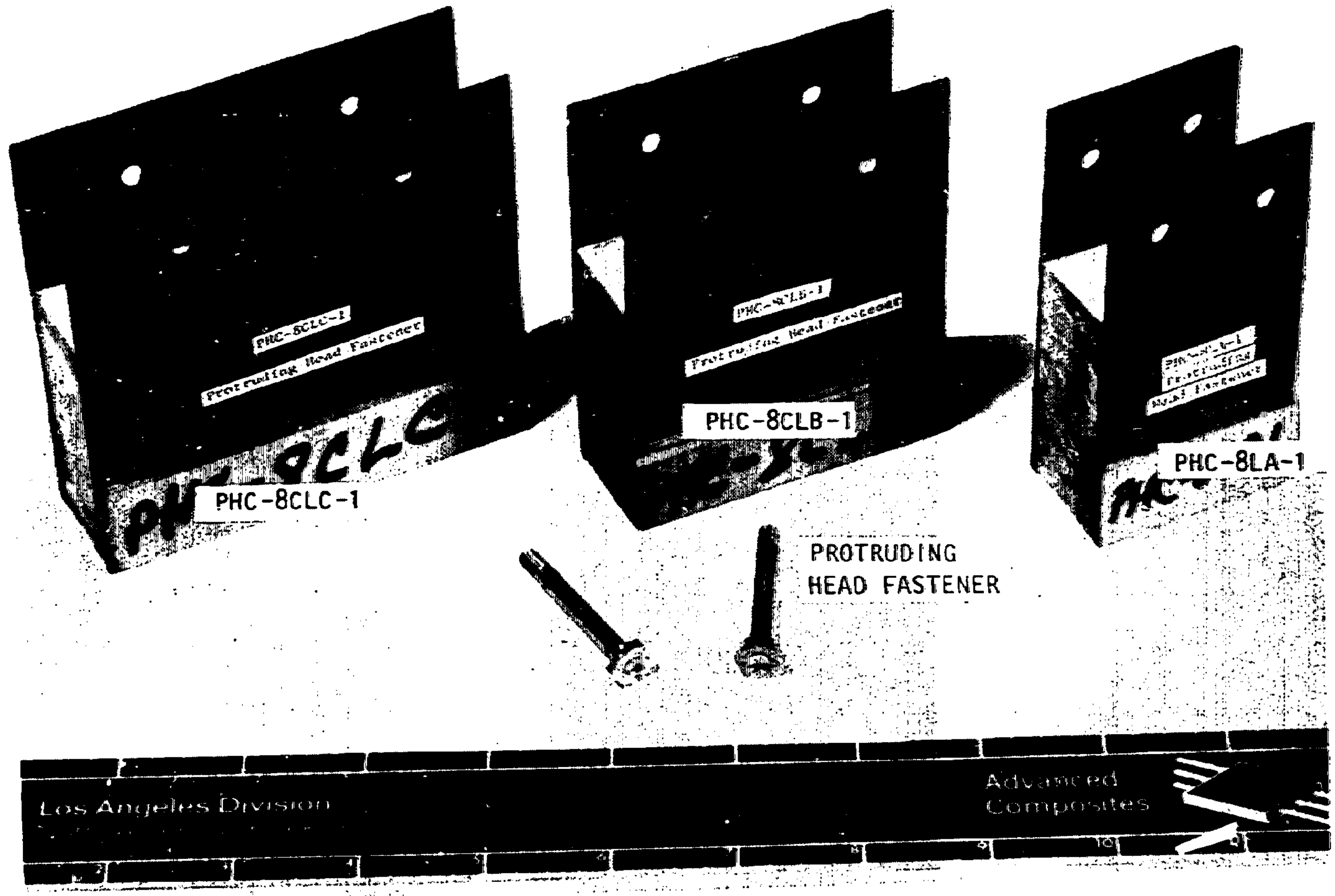


Figure 148. Typical Failed Graphite/Epoxy Compression Mechanical Joint Specimens (Protruding Head Fasteners)

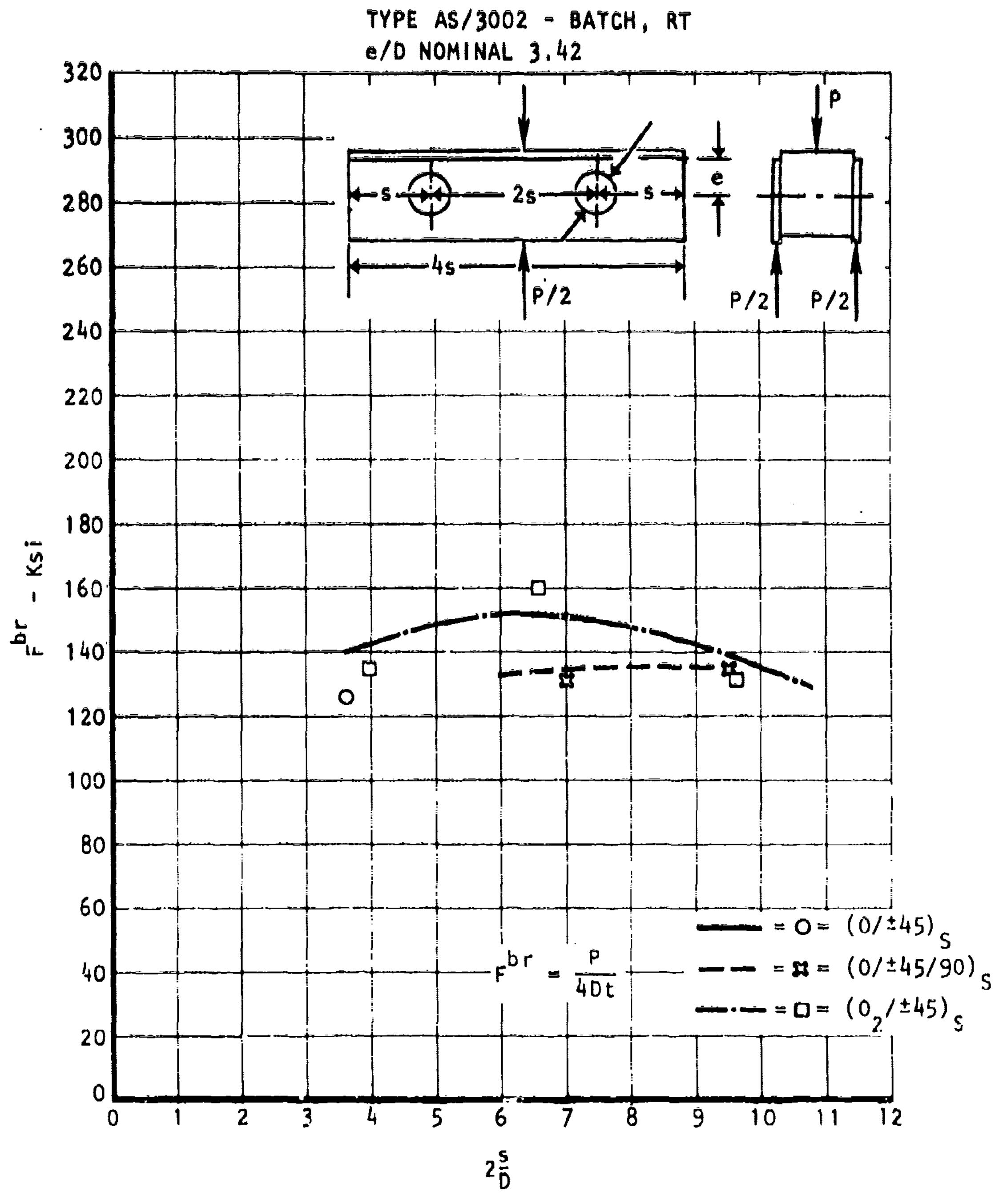


Figure 149. Bearing Strength Versus Fastener Spacing to Fastener Diameter Ratio for Protruding Head Fastener Graphite/Epoxy to Aluminum Single Lap Mechanical Joints - Room Temperature

Tension Fatigue - Flush-Head Fastened Mechanical Joint

Treated Graphite/Epoxy (Type AS/3002) to Steel

Table LVII presents room-temperature tension fatigue (R=0.05) data for single lap mechanical graphite/epoxy to steel joints. NAS 1153 (160 to 180 Ksi heat-treat) flush-head fasteners, as well as e/D and s/D ratios of 2.63 (nominal), were used on all test specimens. $[0/\pm45]_{4S}$, $[0/\pm45/90]_{2S}$, and $[0_2/\pm45]_{2S}$ graphite/epoxy laminate orientations were used. In general, the specimens that failed had a combination bearing and secondary fastener failure, with the exception of specimen FFHT-16LA5 where the fastener pulled through the laminate. Note that the specimens indicated as no failure (runouts) were run to 2.5×10^6 cycles and the test stopped. Figure 150 shows the typical test setup, while figure 151 presents photographs of typical failed specimens.

The test bearing stresses are also plotted versus cycles to failure in figure 152. An examination of this plot shows that the fatigue S-N curves for the flush-head mechanical joints are fairly flat. Also, at 10^4 cycles and greater there appears to be little difference in fatigue bearing strength for the various crossplied orientations tested. The fatigue bearing strengths for the flush-head fastener were also found to be about 45 percent lower than those for comparable protruding-head fastener test specimens. (See figure 153.) Using 10^6 cycles as an arbitrary fatigue limit, the joint fatigue limit value for the three orientations would be at least 60 percent of static joint strength.

TABLE LVII. GRAPHITE/EPOXY TO STEEL SINGLE LAP FLUSH FASTENER MECHANICAL JOINT (*) ROOM TEMPERATURE TENSION FATIGUE DATA (TYPE AS/3002, BATCH) R=0.05, 95 TO 100 CPS, $e/D = s/D = 2.63$ (NOMINAL)

Specimen Number	Orientation	D** (in.)	t (in.)	$\frac{D}{t}$	Max Load (lb)	% of Avg Static	F^{br} (Ksi)	Cycles to Failure	$F^{tu} = F^{su}$ (Ksi)	Failure Mode***
Avg Static	$[0/\pm45]_{4S}$	0.19	---	--	2,237	100	--	Static	--	--
FFHT-24LA1	$[0/\pm45]_{4S}$	0.19	0.1520	1.25	1,790	88	61.98	6.48×10^4	14.55	B, F
FFHT-24LA2	$[0/\pm45]_{4S}$	0.19	0.1497	1.27	1,700	76	59.77	3.96×10^4	14.03	B, F
FFHT-24LA3	$[0/\pm45]_{4S}$	0.19	0.1470	1.29	1,454	65	52.06	1.96×10^5	12.22	B, F
FFHT-24LA4	$[0/\pm45]_{4S}$	0.19	0.1476	1.29	1,342	60	47.85	8.75×10^5	11.23	B, F
FFHT-24LA5	$[0/\pm45]_{4S}$	0.19	0.1530	1.24	1,901	85	65.39	1.06×10^4	15.35	B, F
Avg Static	$[0/\pm45/90]_{2S}$	0.19	--	--	1,537	100	--	Static	--	--
FFHT-16LA1	$[0/\pm45/90]_{2S}$	0.19	0.0929	2.05	1,230	80	69.68	20	16.36	B
FFHT-16LA2	$[0/\pm45/90]_{2S}$	0.19	0.0940	2.02	1,076	70	60.25	2.5×10^6	14.14	NF
FFHT-16LA3	$[0/\pm45/90]_{2S}$	0.19	0.0946	2.01	1,153	75	64.15	2.5×10^6	15.05	NF
FFHT-16LA4	$[0/\pm45/90]_{2S}$	0.19	0.0918	2.07	1,230	80	70.52	0	16.55	B
FFHT-16LA5	$[0/\pm45/90]_{2S}$	0.19	0.0942	2.02	1,200	78	67.05	8.6×10^3	15.74	P
Avg Static	$[0_2/\pm45]_{2S}$	0.19	--	--	1,208	100	--	Static	--	--
FFHT-16CLA1	$[0_2/\pm45]_{2S}$	0.19	0.1070	1.78	966	80	47.52	4.73×10^5	11.16	B, F
FFHT-16CLA2	$[0_2/\pm45]_{2S}$	0.19	0.1022	1.86	906	75	46.66	2.5×10^6	10.95	NF
FFHT-16CLA3	$[0_2/\pm45]_{2S}$	0.19	0.1021	1.86	1,027	85	52.94	2.5×10^6	12.43	NF
FFHT-16CLA4	$[0_2/\pm45]_{2S}$	0.19	0.0929	2.05	1,148	95	65.04	5.1×10^4	15.27	B, F
FFHT-16CLA4	$[0_2/\pm45]_{2S}$	0.19	0.1034	1.84	1,087	90	53.33	2.5×10^6	12.99	NF

*Fastener: flush-head NAS 1153 (160,000 to 180,000 psi - heat treat)

**Nominal

***Failure Modes: B = bearing, F = fastener, P = fastener pulled through laminate
T = net tension, S = shearout, NF = no failure

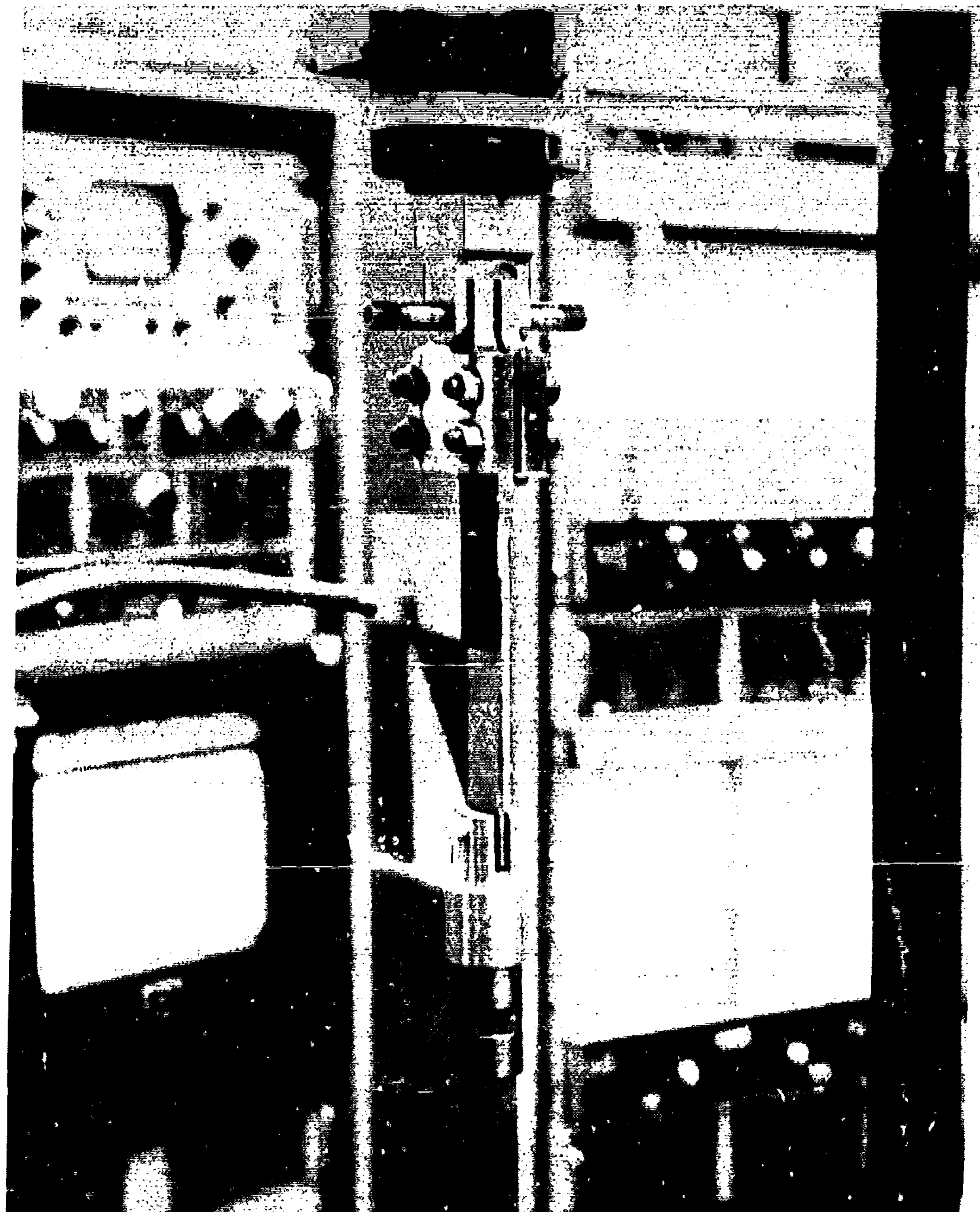
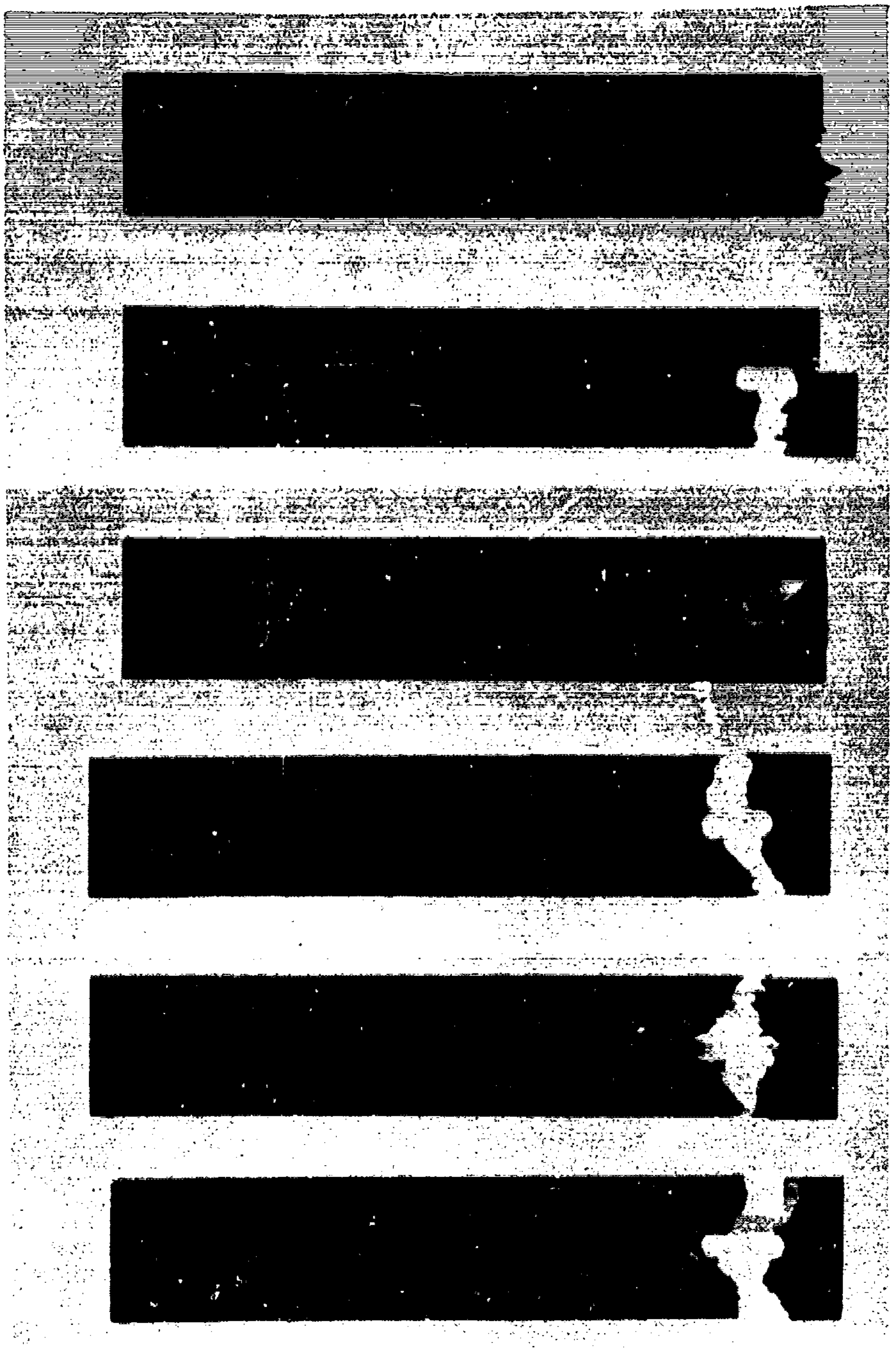


Figure 150. Test Setup for Mechanical Joint Fatigue Tests



FHT16CLA

PHT8CLA

FHT24LA

PHT6LA

FHT16LA

PHT8LA

Figure 151. Typical Failed Mechanical Joint Fatigue Specimens - Flush Head and Protruding Head Fastener Types

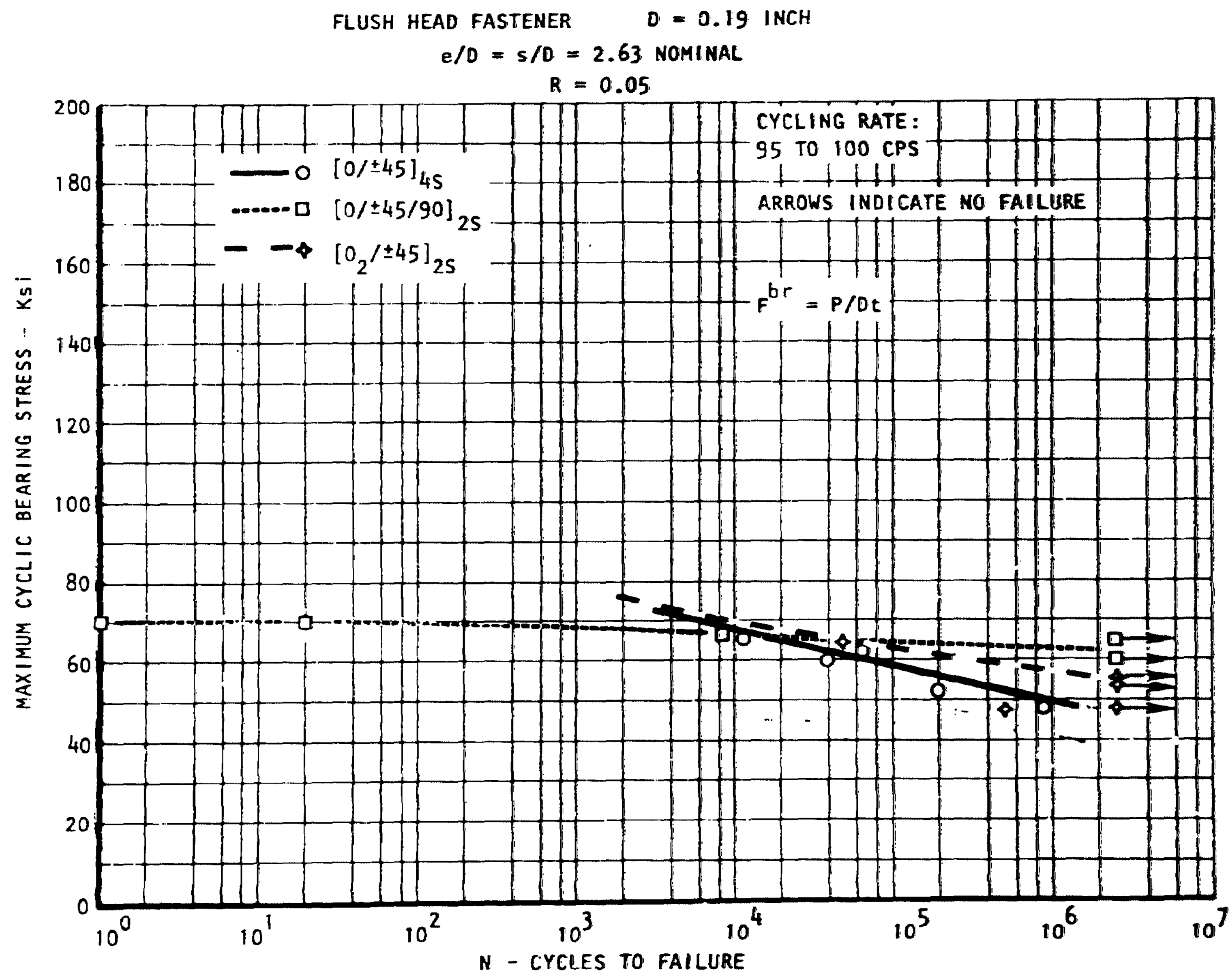


Figure 152. Room Temperature Fatigue S-N Curves for Various Crossplied Graphite/Epoxy to Steel Single Lap Flush Head Mechanical Joints (Type AS/3002, Batch Graphite/Epoxy)

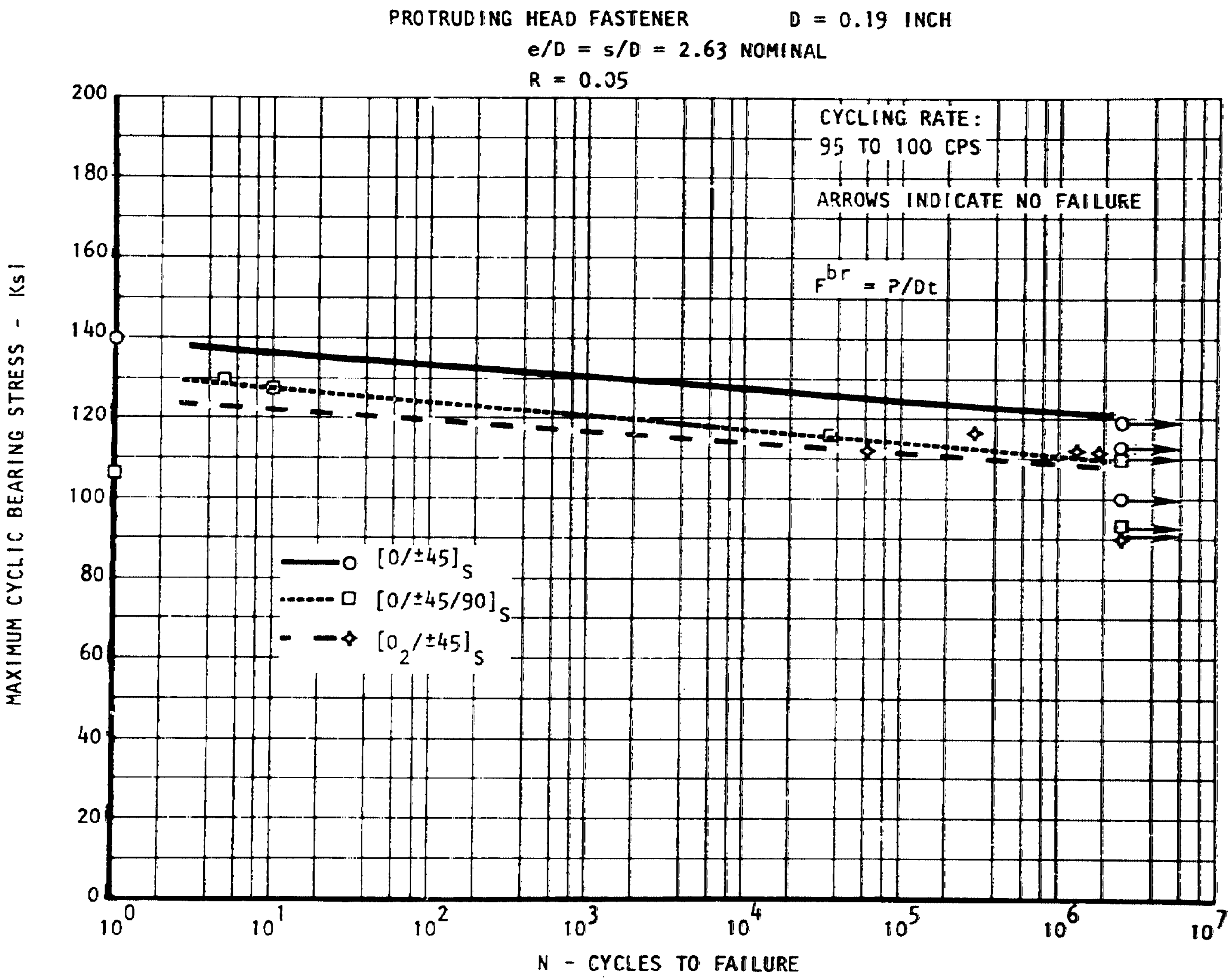


Figure 153. Room Temperature Fatigue S-N Curves for Various Crossplied Graphite/Epoxy to Steel Single Lap Protruding Head Mechanical Joints (Type AS/3002, Batch Graphite/Epoxy)

Tension Fatigue - Protruding-Head Fastened Mechanical Joint

Treated Graphite/Epoxy (Type AS/3002) to Steel

Room-temperature tension fatigue ($R=0.05$) data for single lap mechanical graphite/epoxy (Type AS/3002, batch) to steel joints, with protruding head fasteners (NAS 1103 - 160 to 180 Ksi heat-treat), are presented in table LVIII. All specimens had e/D and s/D ratios of 2.63 (nominal), which corresponded to the flush-head fatigue mechanical joint specimens reported in table LVII. All failures were of the bearing type. Note that all specimen tests were stopped at 2.5×10^6 cycles if no failure had occurred prior to that number of cycles. Typical failed specimens are shown in figure 151.

Figure 153 presents a plot of bearing stress versus number of cycles to failure for the protruding head joints. As in the case of the flush-head joints, there appeared to be little variation in joint fatigue strength for the orientations tested. Furthermore, as previously noted, the protruding head joints possessed about twice the fatigue bearing strength capability of comparable flush-head joints. The curves were also very "flat" over a range of 10 to 10^6 cycles, showing a superior fatigue behavior to all-metal joints. Also, there appeared to be only about an 8-percent reduction over static strength even at 2.5×10^6 cycles. (Compare Tables LII through LIV with table LVIII.) A joint fatigue limit of at least 70 percent of static joint strength is evident for all the laminate orientations tested.

TABLE LVIII. GRAPHITE/EPOXY TO STEEL SINGLE LAP MECHANICAL JOINT (*) ROOM TEMPERATURE TENSION FATIGUE DATA (TYPE AS/3002, BATCH) R=0.05, 95 TO 100 CPS, $e/_D = s/_D = 2.63$ (NOMINAL)

Specimen Number	Orientation	D** (in.)	t (in.)	$\frac{D}{t}$	Max Load (lb)	% of Avg Static Load	F^{br} (Ksi)	Cycles to Failure	$F^{tu} = F^{su}$	Failure Mode***
Avg Static	$[0/\pm45]_S$	0.19	0.0360	5.28	873	100	127.63	Static	29.96	B
FPHT-6LA1	$[0/\pm45]_S$	0.19	0.0369	5.15	655	75	93.43	2.5×10^6	21.93	1
FPHT-6LA2	$[0/\pm45]_S$	0.19	0.0376	5.05	716	82	100.22	2.5×10^6	23.53	1
FPHT-6LA3	$[0/\pm45]_S$	0.19	0.0363	5.23	786	90	113.96	2.5×10^6	26.75	1
FPHT-6LA4	$[0/\pm45]_S$	0.19	0.0375	5.07	847	97	118.88	2.5×10^6	27.91	1
FPHT-6LA5	$[0/\pm45]_S$	0.19	0.0374	5.08	994	114	139.88	2	32.84	B
Avg Static	$[0/\pm45/90]_S$	0.19	--	--	1,405	100	--	Static	--	B
FPHT-8LA1	$[0/\pm45/90]_S$	0.19	0.0455	4.18	1,124	80	130.02	5	30.52	B
FPHT-8LA2	$[0/\pm45/90]_S$	0.19	0.0434	4.38	1,054	75	127.82	10	30.01	B
FPHT-8LA3	$[0/\pm45/90]_S$	0.19	0.0437	4.35	913	65	109.96	2.5×10^6	25.81	1
FPHT-8LA4	$[0/\pm45/90]_S$	0.19	0.0446	4.26	984	70	116.12	3.48×10^4	27.26	B
FPHT-8LA5	$[0/\pm45/90]_S$	0.19	0.0447	4.25	900	64	105.97	3	24.88	B

TABLE LVIII. GRAPHITE/EPOXY TO STEEL SINGLE LAP MECHANICAL JOINT (*) ROOM TEMPERATURE TENSION FATIGUE DATA (TYPE AS/3002, BATCH) R=0.05, 95 TO 100 CPS, $e/_D=s/_D=2.63$ (NOMINAL) - Concluded

Specimen Number	Orientation	D** (in.)	t (in.)	$\frac{D}{t}$	Max Load (lb)	% of Avg Static Load	F^{br} (Ksi)	Cycles to Failure	$F^{tu}=F^{su}$	Failure Mode***
Avg Static	$[0_2/\pm45]_S$	0.19	--	--	1,258	100	--	Static	--	B
FPHT-8CLA1	$[0_2/\pm45]_S$	0.19	0.0500	3.80	1,107	88	116.53	$3.11x10^5$	27.35	B
FPHT-8CLA2	$[0_2/\pm45]_S$	0.19	0.0487	3.90	1,040	82.5	112.40	$1.19x10^6$	26.39	B
FPHT-8CLA3	$[0_2/\pm45]_S$	0.19	0.0505	3.76	1,070	85	111.52	$6.17x10^4$	26.18	B
FPHT-8CLA4	$[0_2/\pm45]_S$	0.19	0.0470	4.04	1,006	80	112.65	$1.14x10^6$	26.44	B
FPHT-8CLA5	$[0_2/\pm45]_S$	0.19	0.0505	3.75	875	69.5	91.19	$2.5x10^6$	21.41	NF

*Fastener: protruding head NAS 1103 (160,000 to 180,000 psi - heat-treat)
**Nominal
***Failure modes: B = bearing, F = fastener, P = fastener pulled through laminate
T = net tension, S = shearout

(1) No failure - Runout

(3) Failed in loading at 900 lb

(2) Failed in loading

CONFIGURATION DATA

CORE DENSITY VARIATION SANDWICH BENDING BEAMS

Tension Bending Beams - Single-Stage Bonded

Table LIX presents tension bending beam data for beams with various crossplied Type AS/3002 batch graphite/epoxy face sheets. In all cases, the face sheets were single stage bonded (cured during bonding to 3/16-inch cell honeycomb core). Both $[0/\pm45/90]_s$ and $[0/\pm45]_s$ orientations were used. In addition, a $[0/\pm45]_s$ laminate plus a 7581 fiberglass ply was also tested. In all cases, three core densities were used, these being 3.1, 4.4, and 5.7 pcf. Tests were run at room temperature and 350°F for each orientation and core density. All room temperature failures were laminate tension failures, whereas the 350°F failures were face sheet-to-core bond failures. Typical failed specimens are shown in figures 154 through 156.

In general, there appeared to be little variation in room temperature tension strength due to core density variation. The 350°F strengths, likewise, did not vary much with core density, but the data are not conclusive as all elevated temperature specimens failed in the face sheet-to-core bond rather than laminate tension failure. The room temperature stengths also compared well with predicted values (section V), with the $[0/\pm45]_s$ plus 7581 fiber glass ply laminate exceeding predicted strength by 28 percent.

In summary, tension bending beam strengths appeared to be unaffected by core density variation. Compared to strengths obtained from secondary bonded tension bending beams (table XX), however, the single stage bonded (cocured) beams had a 25-percent reduction in ultimate strength. This reduction in strength level for cocured sandwich specimens has also been noted in reference 11.

TABLE LIX. CROSSPLIED GRAPHITE/EPOXY TENSION SANDWICH BEAM DATA - CORE DENSITY VARIATION - SINGLE STAGE BONDED - TYPE AS/3002 BATCH

Orientation	Specimen No.	Temp (°F)	Core Density (pfc)*	Test Stress (Ksi)	Failure Mode**	Predicted Stress*** (Ksi)	Test/ Predicted Stress
$[0/\pm45/90]_S$	TWS-8L3-1	RT	3.1	60.19	T	64	0.940
	TWS-8L4-1	RT	4.4	59.22	T	64	0.925
	TWS-8L5-1	RT	5.7	65.58	T	64	1.025
	Avg			(61.66)			(0.963)
	TWS-8L3-2	350	3.1	33.34	B	54	0.617
	TWS-8L4-2	350	4.4	35.67	B	54	0.661
	TWS-8L5-2	350	5.7	43.63	B	54	0.808
	Avg			(37.35)			(0.695)
$[0/\pm45]_S$	TWS-6L3-1	RT	3.1	77.27	T	70	1.104
	TWS-6L4-1	RT	4.4	77.67	T	70	1.110
	TWS-6L5-1	RT	5.7	65.77	T	70	0.940
	Avg			(73.57)			(1.051)
	TWS-6L3-2	350	3.1	50.92	B	57	0.893
	TWS-6L4-2	350	4.4	51.98	B	57	0.911
	TWS-6L5-2	350	5.7	52.37	B	57	0.919
	Avg			(51.76)			(0.908)

TABLE LIX. CROSSPLIED GRAPHITE/EPOXY TENSION SANDWICH BEAM DATA - CORE DENSITY VARIATION - SINGLE STAGE BONDED - TYPE AS/3002 BATCH (CONCLUDED)

Orientation	Specimen No.	Temp (°F)	Core Density (pfc)*	Test Stress (Ksi)	Failure Mode**	Predicted Stress*** (Ksi)	Test/ Predicted Stress
$[0/\pm45]_S$ + Fiber Glass one ply 7581****	TWS-6LG3-1	RT	3.1	99.21	T	70	1.417
	TWS-6LG4-1	RT	4.4	86.37	T	70	1.233
	TWS-6LG5-1	RT	5.7	83.34	T	70	1.191
	Avg			(89.64)			(1.281)
	TWS-6LG3-2	350	3.1	43.87	B	57	0.770
	TWS-6LG4-2	350	4.4	48.16	B	57	0.845
	TWS-6LG5-2	350	5.7	58.04	B	57	1.018
	Avg			(50.02)			(0.878)

*3/16-inch cell aluminum honeycomb nominal core density
**T = face sheet tension; B = bond failure
***Predicted values (refer to section V)
****Fiber glass thickness not included in stress level calculations

NOTE Load orientation - longitudinal tension.

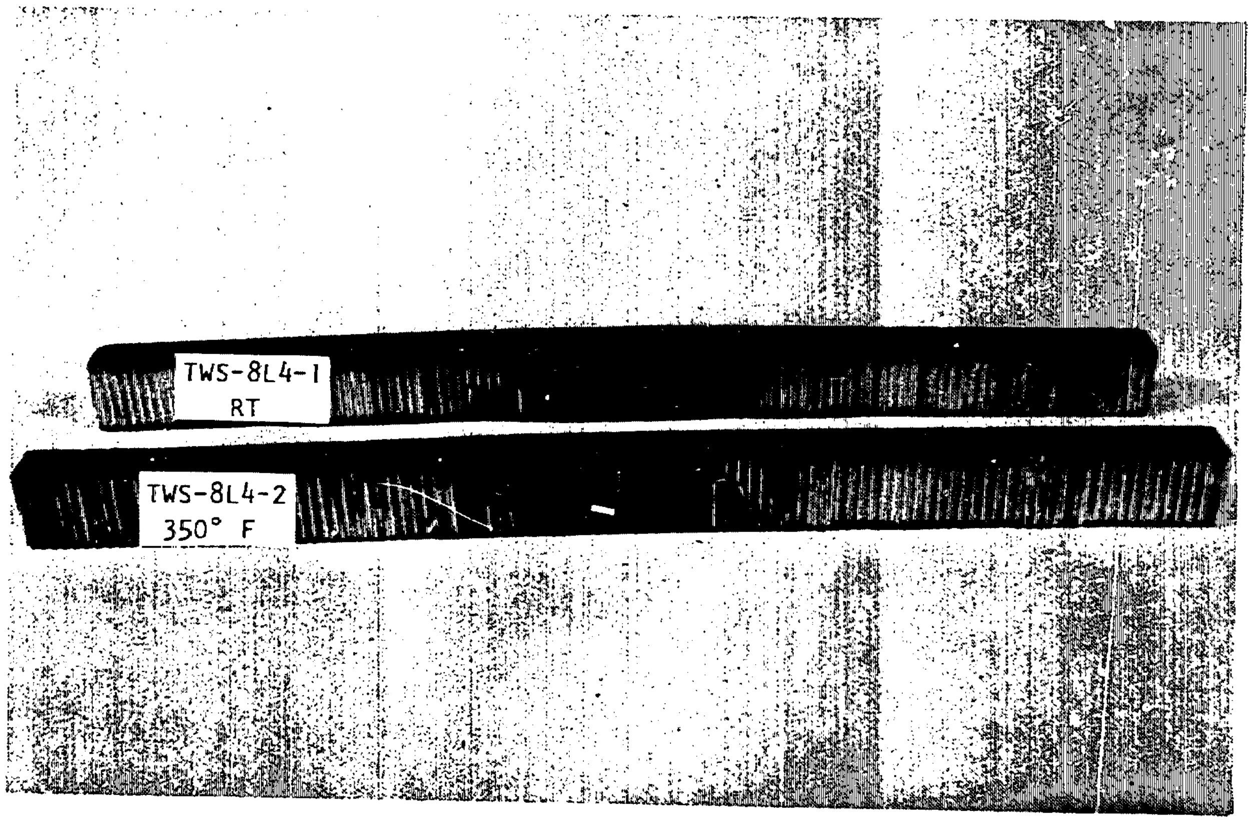


Figure 154. Tension Sandwich Bending Beams With Type AS/3002 Batch Graphite/Epoxy Face Sheets, $[0/\pm 45/90]_S$ Single Stage Bonded

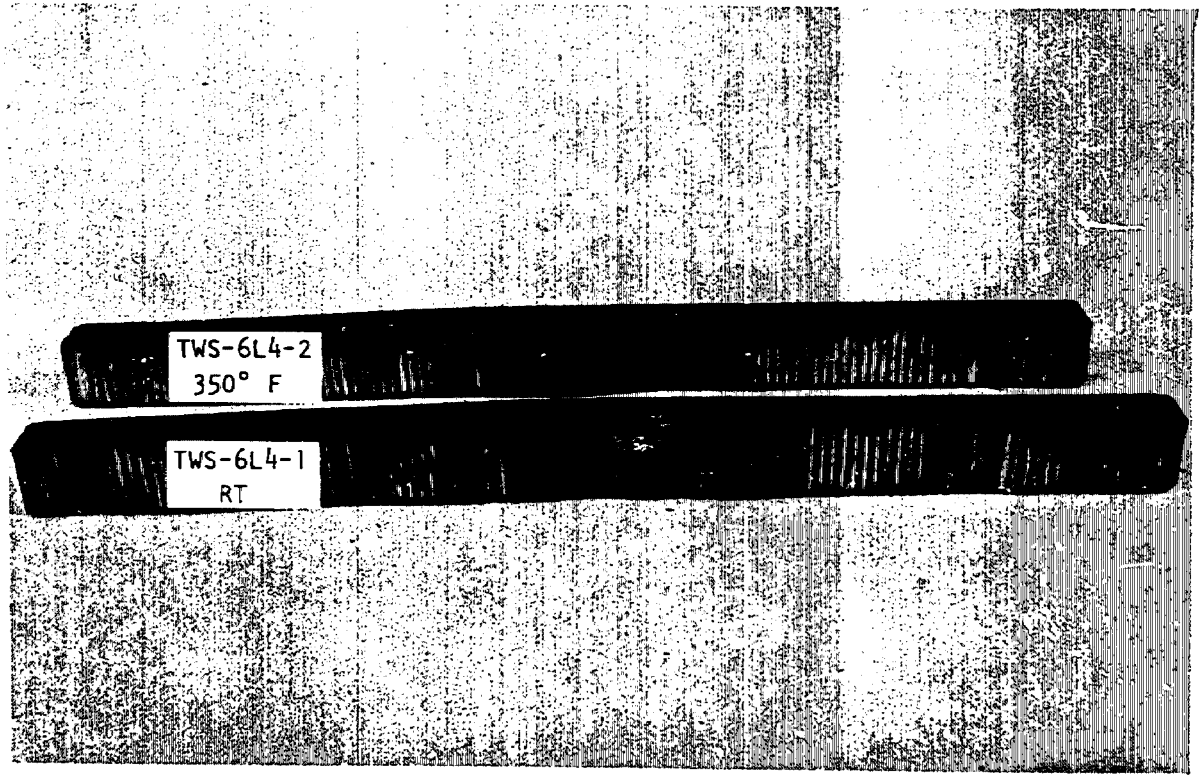


Figure 155. Tension Sandwich Bending Beams With Type AS/3002 Batch Graphite/Epoxy Face Sheets, $[0/\pm45]_S$ Single Stage Bonded

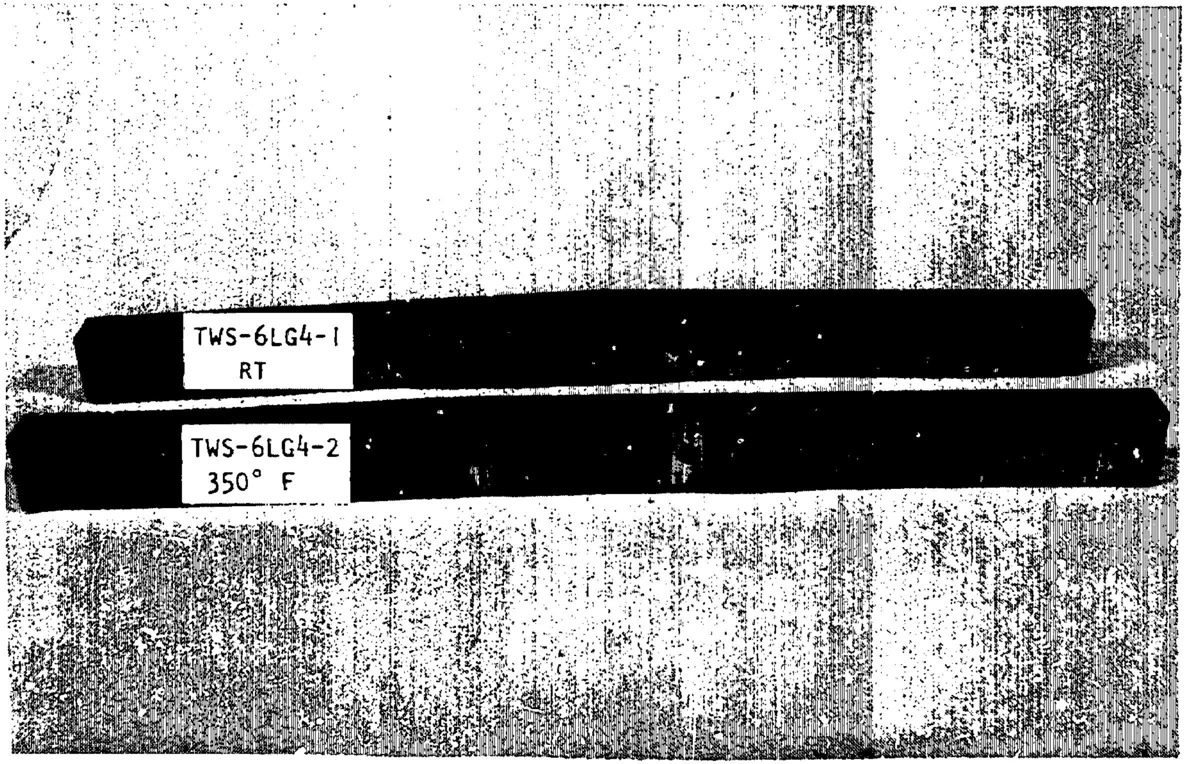


Figure 156. Tension Sandwich Bending Beams With Type AS/3002 Batch Graphite/Epoxy Face Sheets, $[0/\pm 45]_S$ Plus Fiber Glass Ply - Single Stage Bonded

Compression Bending Beams - Single-Stage Bonded

Table LX and LXI summarize test data for single stage bonded sandwich compression beams with core density variations. The face sheets tested were $[0/\pm45]_S$ and $[0/\pm45/90]_S$ graphite/epoxy laminates, as well as $[0/\pm45]_S$ graphite/epoxy plus one ply of fiber glass. Both room temperature and 350°F tests were run, and typical failed specimens are shown in figures 157, 158, and 159. For the most part, the failures were of the laminate compression mode, with the exceptions being some of the room temperature and 350°F $[0/\pm45]_S$ plus fiber glass laminates, and all of the 350°F $[0/\pm45/90]_S$ laminates which were face sheet to core bond failures.

Figures 160 and 161 present graphical plots of the data. In general, the figures show that, if the invalid bond failure points are ignored, there is little or no variation in compression strength due to core density variations. The test values also compared fairly well with predicted values (section V), although they were somewhat lower than the "secondary bonded" compression beam strength values shown in tables LXII and LXIII. Secondary face sheet bonding then, appears to have the strength advantage over single stage bonding. This could possibly be because "dimpling" of the face sheet can occur in single stage bonding, hence lowering the face sheet strength capabilities.

TABLE LX. CROSSPLIED GRAPHITE/EPOXY COMPRESSION SANDWICH BEAM DATA - CORE DENSITY VARIATION - SINGLE STAGE BONDED - TYPE AS/3002 BATCH - $[0/\pm45]_S$ AND $[0/\pm45]_S$ + FIBER GLASS

Orientation	Specimen No.	Temp (°F)	Core Density (pcf)*	Test Stress (Ksi)	Failure Mode**	Predicted Stress*** (Ksi)	Test/ Predicted Stress
$[0/\pm45]_S$	CWS-63L-1	RT	3.1	75.86	C	73	1.04
	CWS-63L-2	RT	3.1	70.17	C	73	0.96
	CWS-64L-1	RT	4.4	50.15	C	73	0.69
	CWS-64L-2	RT	4.4	63.49	C	73	0.87
	CWS-65L-1	RT	5.7	74.72	C	73	1.02
	CWS-65L-2	RT	5.7	88.38	C	73	1.21
	Avg			(70.46)			(0.97)
	CWS-63L-3	350	3.1	38.46	C	35	1.10
	CWS-64L-3	350	4.4	33.45	C	35	0.96
	CWS-65L-3	350	5.7	33.11	C	35	0.95
	Avg			(35.01)			(1.00)
$[0/\pm45]_S$ + Fiber glass (one ply 7581)	CWS-6LG3-1	RT	3.1	88.85	C	73	1.22
	CWS-6LG3-2	RT	3.1	91.84	C	73	1.26
	CWS-6LG4-1	RT	4.4	96.84	C	73	1.33
	CWS-6LC4-2	RT	4.4	99.08	C	73	1.36
	CWS-6LG5-1	RT	5.7	43.55****	B	73	0.60****
	CWS-6LG5-2	RT	5.7	42.83****	B	73	0.59****
	Avg			(94.15)			(1.29)
	CWS-6LG3-3	350	3.1	25.44	C	35	0.73
	CWS-6LG4-3	350	4.4	31.10	B	35	0.89
	CWS-6LG5-3	350	5.7	9.26****	B	35	0.27****
	Avg			(28.27)			(0.81)

*3/16-inch cell aluminum honeycomb nominal core density
**C = compression failure face sheet; B = bond failure
***Design curves (refer to section V)
****Premature failure specimens CWS-6LG5-1, -2, CWS-6LG5-3), not included in the average
NOTE Load orientation - longitudinal compression

TABLE LXI. CROSSPLIED GRAPHITE/EPOXY COMPRESSION SANDWICH BEAM DATA - CORE DENSITY VARIATION - SINGLE STAGE BONDED - TYPE AS/3002 BATCH - $[0/\pm45/90]_S$

Specimen No.	Temp (°F)	Core Density (pcf)*	Test Stress (Ksi)	Failure Mode**	Predicted Stress*** (Ksi)	Test/ Predicted Stress
CWS-83L-1	RT	3.1	82.00	C	66	1.24
CWS-83L-2	RT	3.1	81.95	C	66	1.24
CWS-84L-1	RT	4.4	72.02	C	66	1.09
CWS-84L-2	RT	4.4	83.19	C	66	1.26
CWS-85L-1	RT	5.7	86.41	C	66	1.31
CWS-85L-2	RT	5.7	53.69	C	66	0.81
Avg			(76.50)			(1.16)
CWS-83L-3	350	3.1	17.83	B	31	0.58
CWS-84L-3	350	4.4	9.85	B	31	0.32
CWS-85L-3	350	5.7	8.78	B	31	0.28
Avg			****			****

*3/16-inch cell aluminum honeycomb nominal core density
**C = compression failure = face sheet; B = bond failure
***Predicted values (refer to section V)
****Premature failure (specimens CWS-83L-3, CWS-84L-3, CWS-85L-3), not included in the average

NOTE Load orientation - longitudinal compression

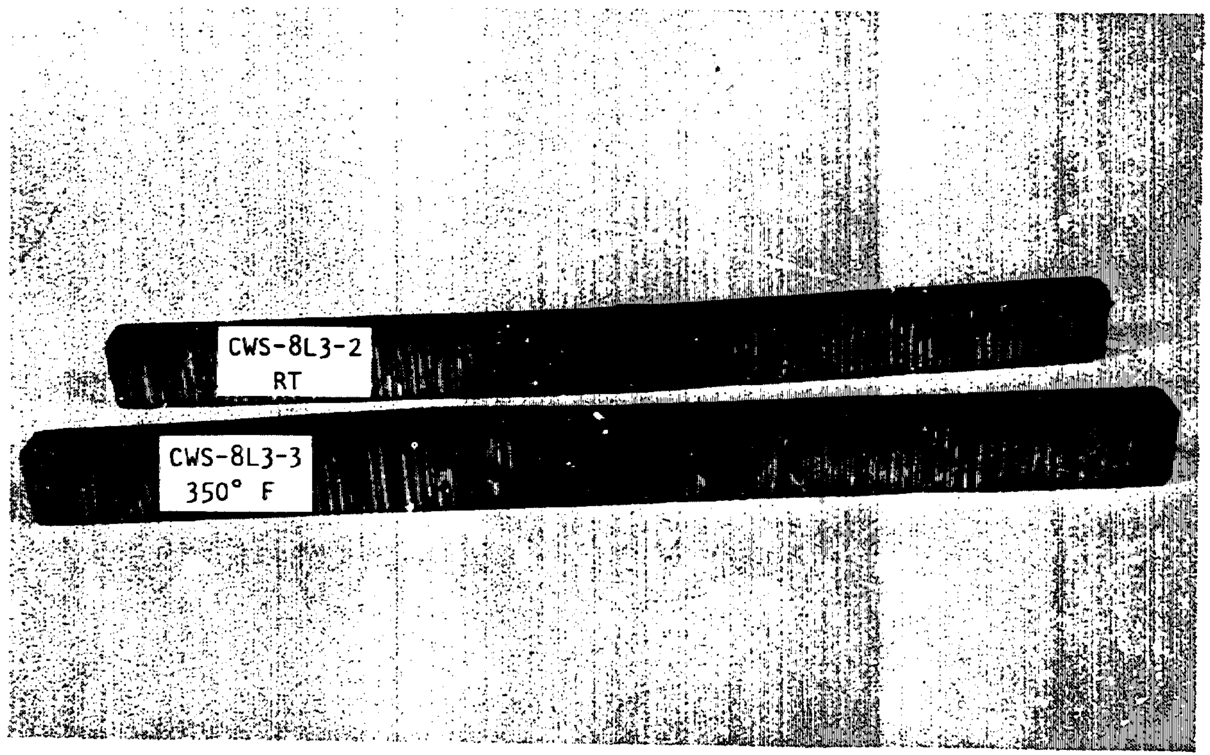


Figure 157. Compression Sandwich Bending Beams With Type AS/3002 Batch Graphite/Epoxy Face Sheets, $[0/\pm 45/90]_S$ Single Stage Bonded

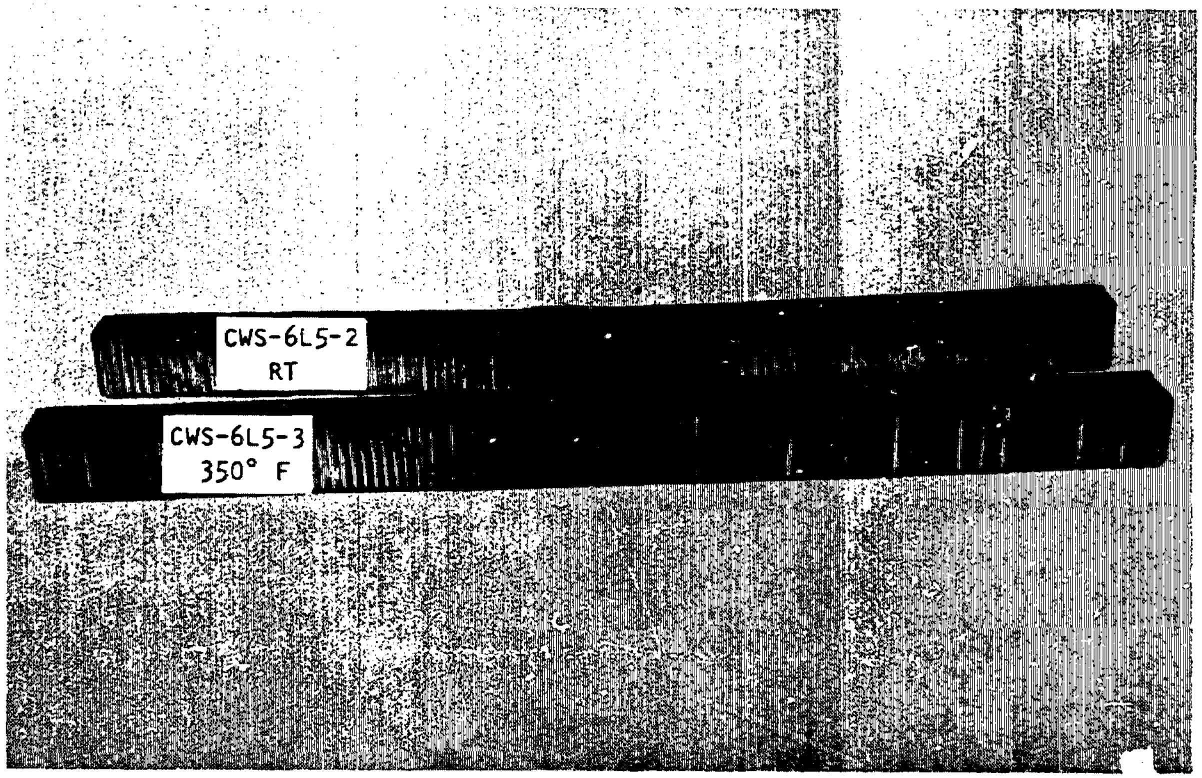


Figure 158. Compression Sandwich Bending Beams With Type AS/3002 Batch Graphite Epoxy Face Sheets, $[0/\pm45]_S$ Single Stage Bonded

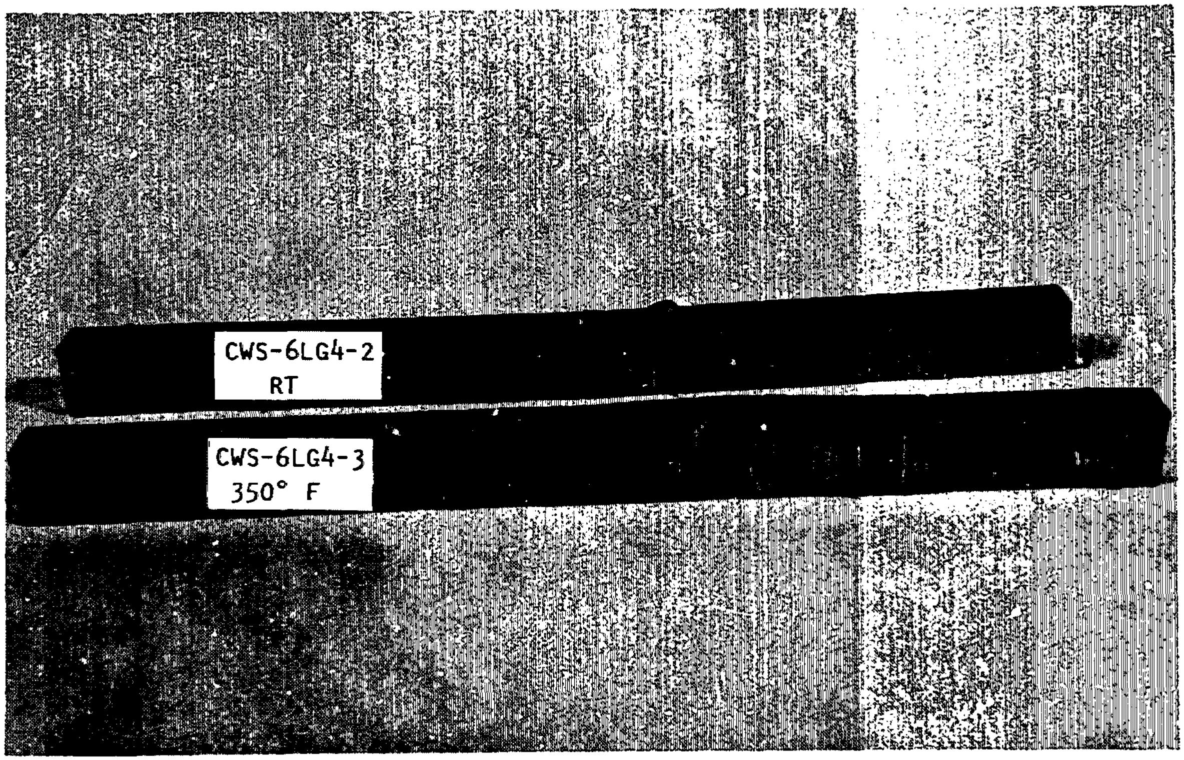


Figure 159. Compression Sandwich Bending Beams With Type AS/3002 Batch Graphite/Epoxy Face Sheets, $[0/\pm 45]_S$, Fiber Glass Ply - Single Stage Bonded

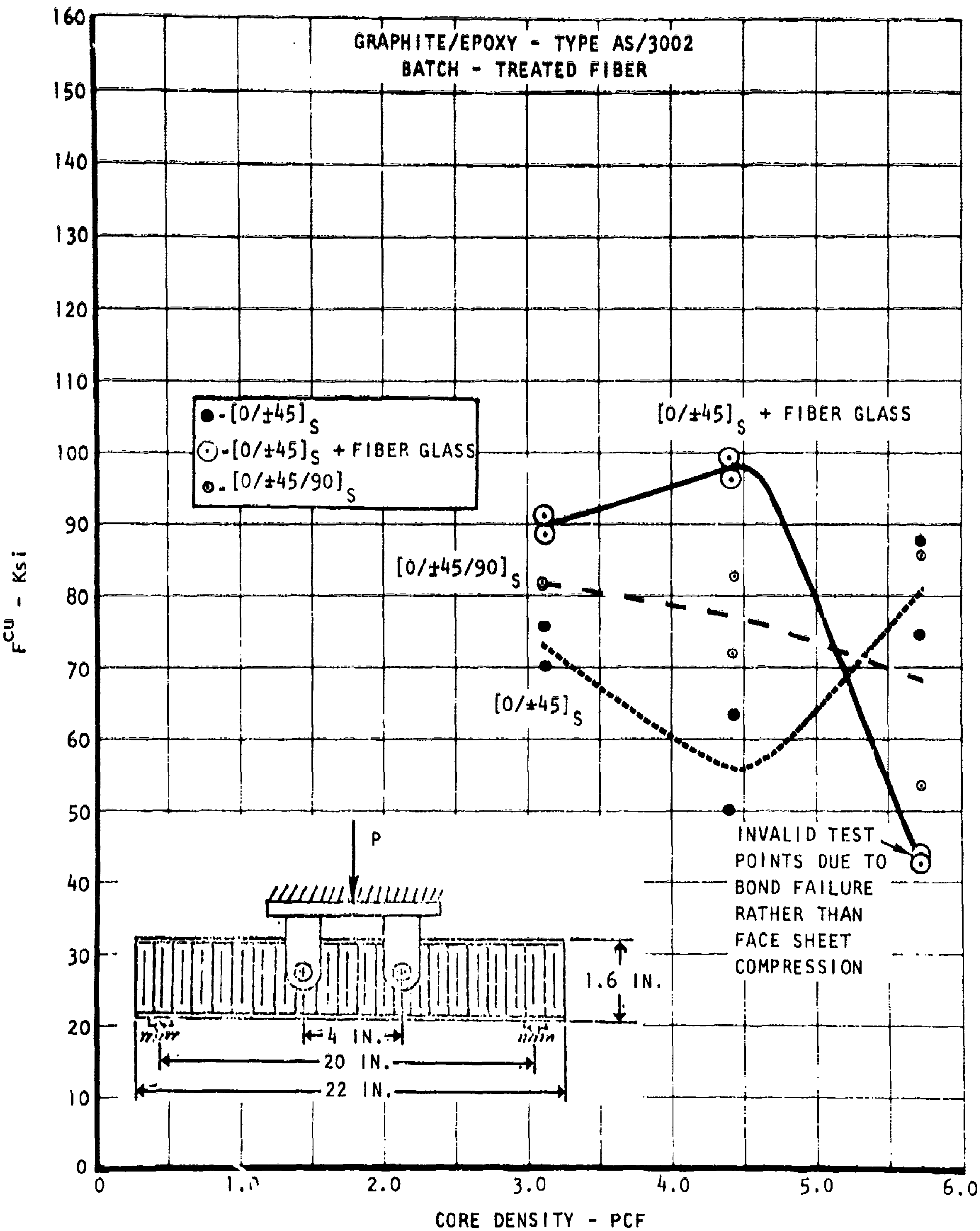


Figure 160. Graphite/Epoxy Sandwich Beam Compression Data - Effect of Core Density and Laminate Orientation - Room Temperature - Single Stage Bonded

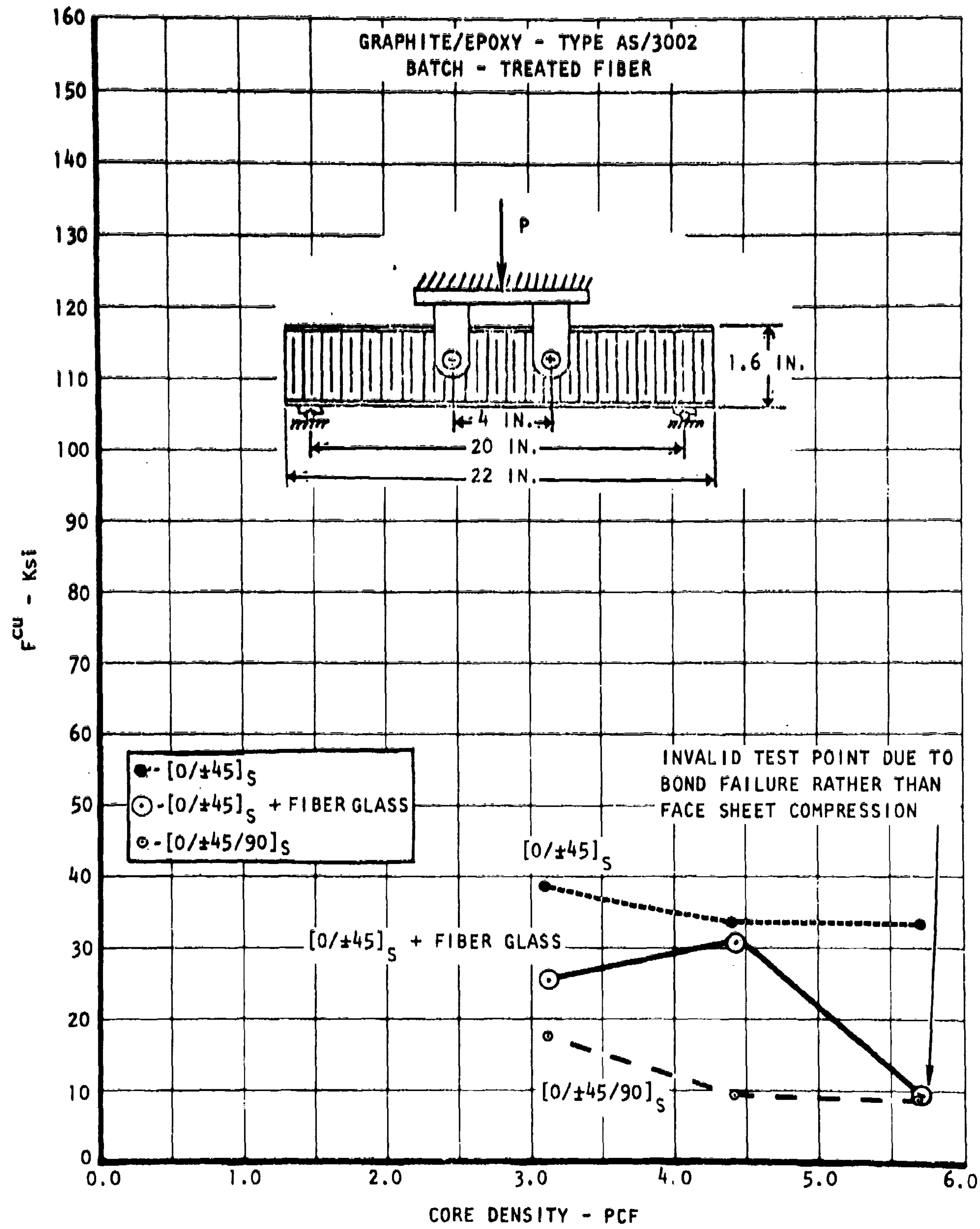


Figure 161. Graphite/Epoxy Sandwich Beam Compression Data - Effect of Core Density and Laminate Orientation, 350° F - Single Stage Bonded

TABLE LXII. CROSSPLIED GRAPHITE/EPOXY COMPRESSION SANDWICH BEAM DATA - CORE DENSITY VARIATION - SECONDARY BONDED - TYPE AS/3002 BATCH - $[0/\pm45]_S$, $[90/\pm45]_S$

Orientation	Specimen No.	Temp (°F)	Core Density (Ksi)*	Test Stress (Ksi)	Predicted Stress** (Ksi)	Test/ Predicted Stress
$[0/\pm45]_S$	CW-631	RT	3.1	91.2	73	1.25
	CW-632	RT	3.1	102.4	73	1.40
	CW-641	RT	4.4	113.5	73	1.56
	CW-642	RT	4.4	104.4	73	1.43
	CW-651	RT	5.7	97.2	73	1.33
	CW-652	RT	5.7	102.0	73	1.40
	Avg			(101.80)	(73)	(1.40)
	CW-633	350	3.1	58.5	35	1.67
	CW-643	350	4.4	71.7	35	2.05
	CW-653	350	5.7	46.5	35	1.33
	Avg			(58.90)	(35)	(1.68)
$[90/\pm45]_S$	CW-6A31	RT	3.1	35.4	40	0.89
	CW-6A32	RT	3.1	34.9	40	0.87
	CW-6A41	RT	4.4	33.4	40	0.84
	CW-6A42	RT	4.4	36.9	40	0.92
	CW-6A51	RT	5.7	33.5	40	0.84
	CW-6A52	RT	5.7	35.3	40	0.88
	Avg			(34.90)	(40)	(0.87)
	CW-6A33	350	3.1	23.8	22	1.08
	CW-6A43	350	4.4	18.0	22	0.82
	CW-6A53	350	5.7	26.8	22	1.22
	Avg			(22.87)	(22)	(1.04)

*3/16-inch cell aluminum honeycomb nominal core density

**Predicted values (refer to section V)

NOTE Load orientation - longitudinal compression

Failure mode - compression failure, face sheet

TABLE LXIII. CROSSPLIED GRAPHITE/EPOXY COMPRESSION SANDWICH BEAM DATA - CORE DENSITY VARIATION - SECONDARY BONDED - TYPE AS/3002 BATCH - $[0/\pm45/90]_S$

Specimen No.	Temp (°F)	Core Density (pcf)*	Test Stress (Ksi)	Predicted Stress** (Ksi)	Test/ Predicted Stress
CW-831	RT	3.1	96.4	66	1.46
CW-832	RT	3.1	90.4	66	1.37
CW-841	RT	4.4	99.7	66	1.51
CW-842	RT	4.4	104.3	66	1.58
CW-851	RT	5.7	109.4	66	1.66
CW-852	RT	5.7	94.7	66	1.43
Avg			(99.15)	(66)	(1.50)
CW-833	350	3.1	39.4	31	1.27
CW-843	350	4.4	26.6	31	0.86
CW-853	350	5.7	32.9	31	1.06
Avg			(32.97)	(31)	(1.06)

*3/16-inch cell aluminum honeycomb nominal core density
**Predicted values (refer to section V)

NOTE Load orientation - longitudinal compression
Failure mode - compression failure, face sheet

Compression Bending Beams - Secondary Bonded

Crossply orientations of [0/±45], [90/±45], and [0/±45/90] were tested as sandwich compression beams with core density variations of 3.1, 4.4, and 5.7 pcf. Typical current data are summarized in tables LXII and LXIII. These specimens had precured graphite/epoxy face sheets which were then secondary bonded to the aluminum honeycomb core. All failure modes were face sheet compression. Typical failed specimens are shown in figures 162 and 163. Figure 163 shows failed compression beam specimens with $[0/\pm45/90]_S$ face sheets and core densities of 3.1, 4.4, and 5.7 pcf, respectively. Figure 162 shows failed compression beam specimens with a 3.1 pcf core and face sheets with three different laminate orientations; namely, $[0/\pm45]_S$, $[90/\pm45]_S$, and $[0/\pm45/90]_S$.

Figures 164 and 165 present the compression strength data at room temperature and 350°F in graphical form for the various laminate orientations and core density variations described in the tables. The concept of increasing core density to increase face sheet compression strength (sandwich wrinkling) was not evident in the range of core density variation (3.1, 4.4, and 5.7 pcf) and crossply orientations, $[0/\pm45]_S$, $[90/\pm45]_S$, and $[0/\pm45/90]_S$ investigated. The 350°F data show an apparent strength increase or decrease for the 4.4 pcf core. A spot check of possible specimen identification error was made but revealed no discrepancies (core cell walls were micrometer measured). The variation in strength levels was attributed to test data scatter. Compared to the single stage bonded compression bending beams with the same face sheet orientations, the secondary bonded beams had compression strengths which were approxmately 50 percent higher, hence indicating some degradation due to single stage bonding, or giving a distinct strength advantage to secondary bonded structures. The data also compared well with predicted values from section V (equaled or exceeded predicted).

OPEN HOLE TESTS

Tension Loaded Open Holes

Open hole room-temperature specimen tension tests were run for the following graphite/epoxy laminate orientations: $[0]_{6T}$, $[0/90]_{2S}$, $[\pm45]_{2S}$, $[0/\pm45]_S$, $[90/\pm45]_S$, $[0/\pm45/90]_S$, $[0_2/\pm45]_S$, and $[90_2/\pm45)_S$. These data are summarized in tables LXIV and LXV. Typical failed specimens are shown in figures 166 and 167.

The test data are also plotted in figures 168 and 169 as net section strength versus percentage of ±45° ply orientations. The trends shown indicate the effect of percentage 0° plies on net stress. The figure and the data both show that net section strength levels are generally reduced from basic "no hole" tension values, resulting in effective net section stress concentration factors, K_t net, ranging from 0.96 to 1.92 for the range of laminate

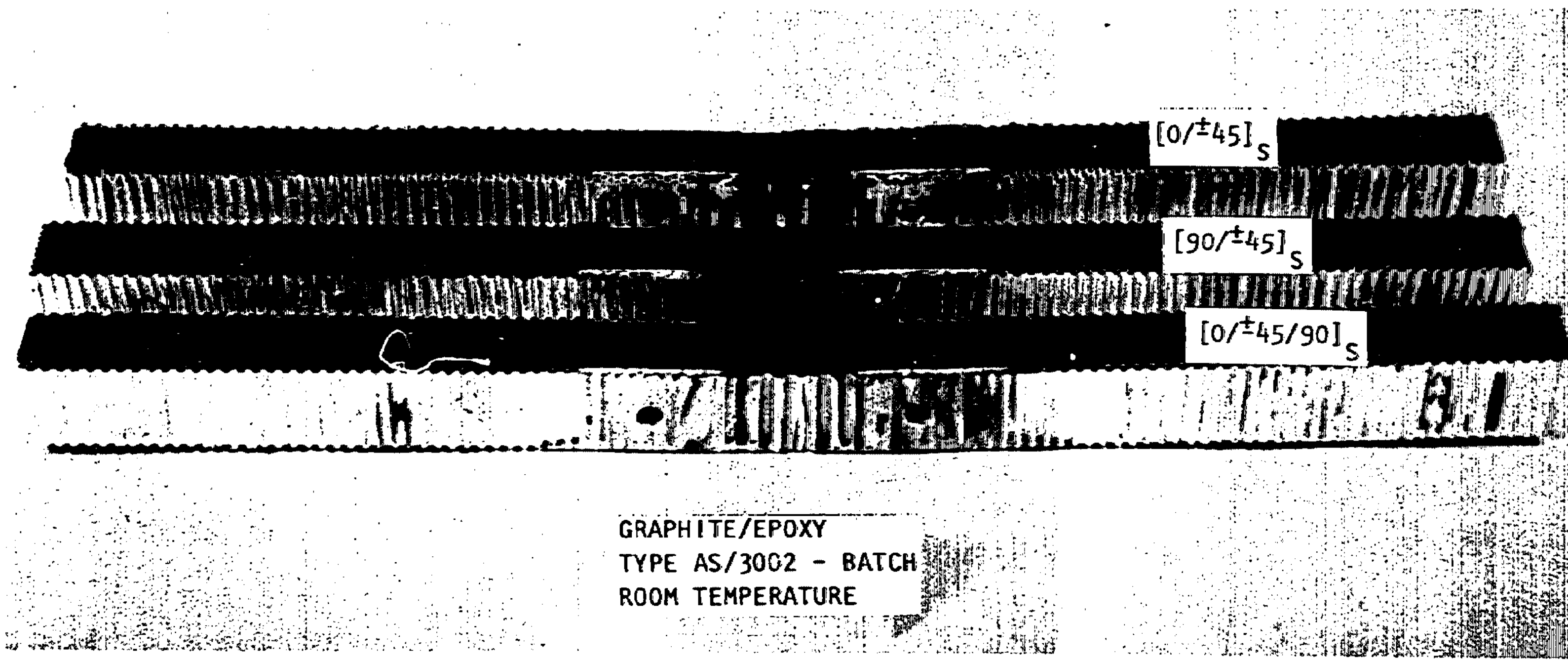


Figure 162. Failed Compression Sandwich Beam Specimens With 3.1 PCF Core and Graphite/Epoxy Face Sheets of Various Orientations: $[0/\pm 45]_S$, $[90/\pm 45]_S$, and $[0/\pm 45/90]_S$

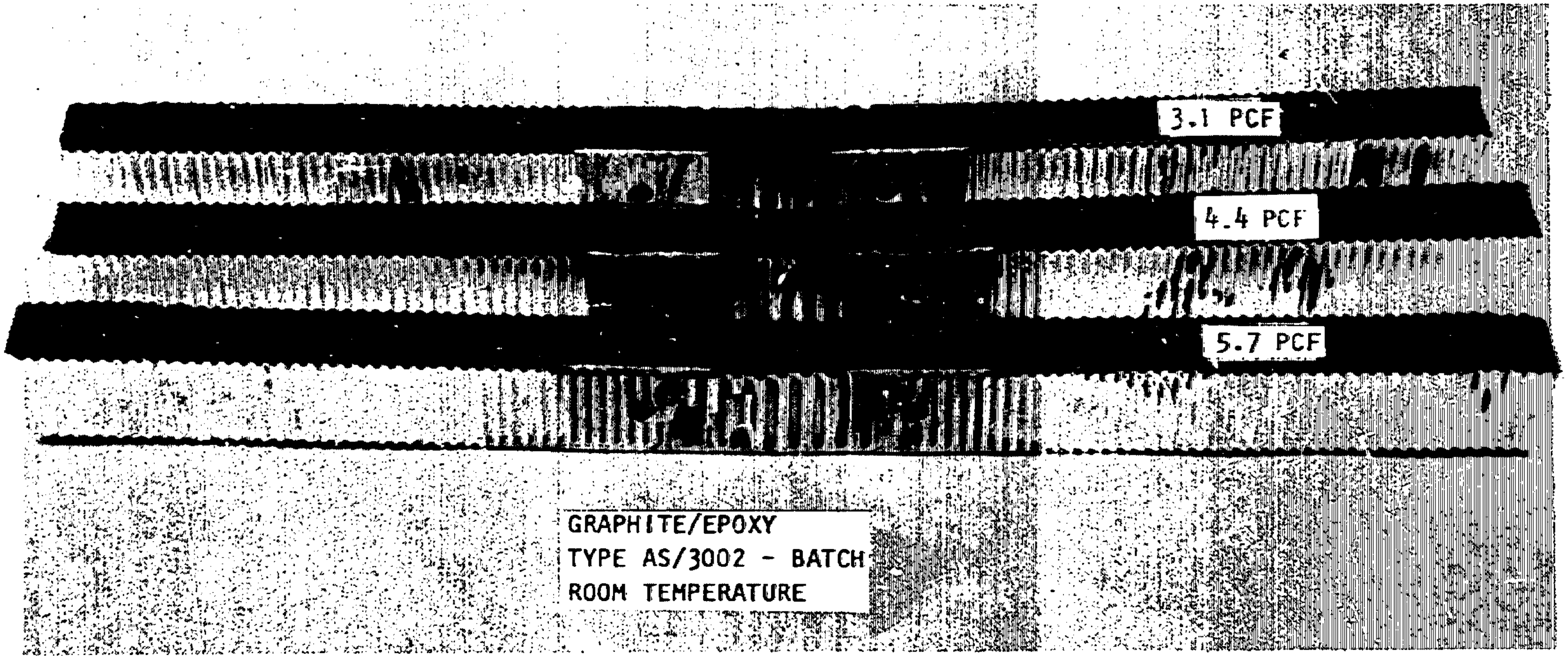


Figure 163. Failed Compression Sandwich Beam Specimens With $[0/\pm 45/90]_S$ Graphite/Epoxy Face Sheets and Various Core Densities (3.1, 4.4, and 5.7 PCF)

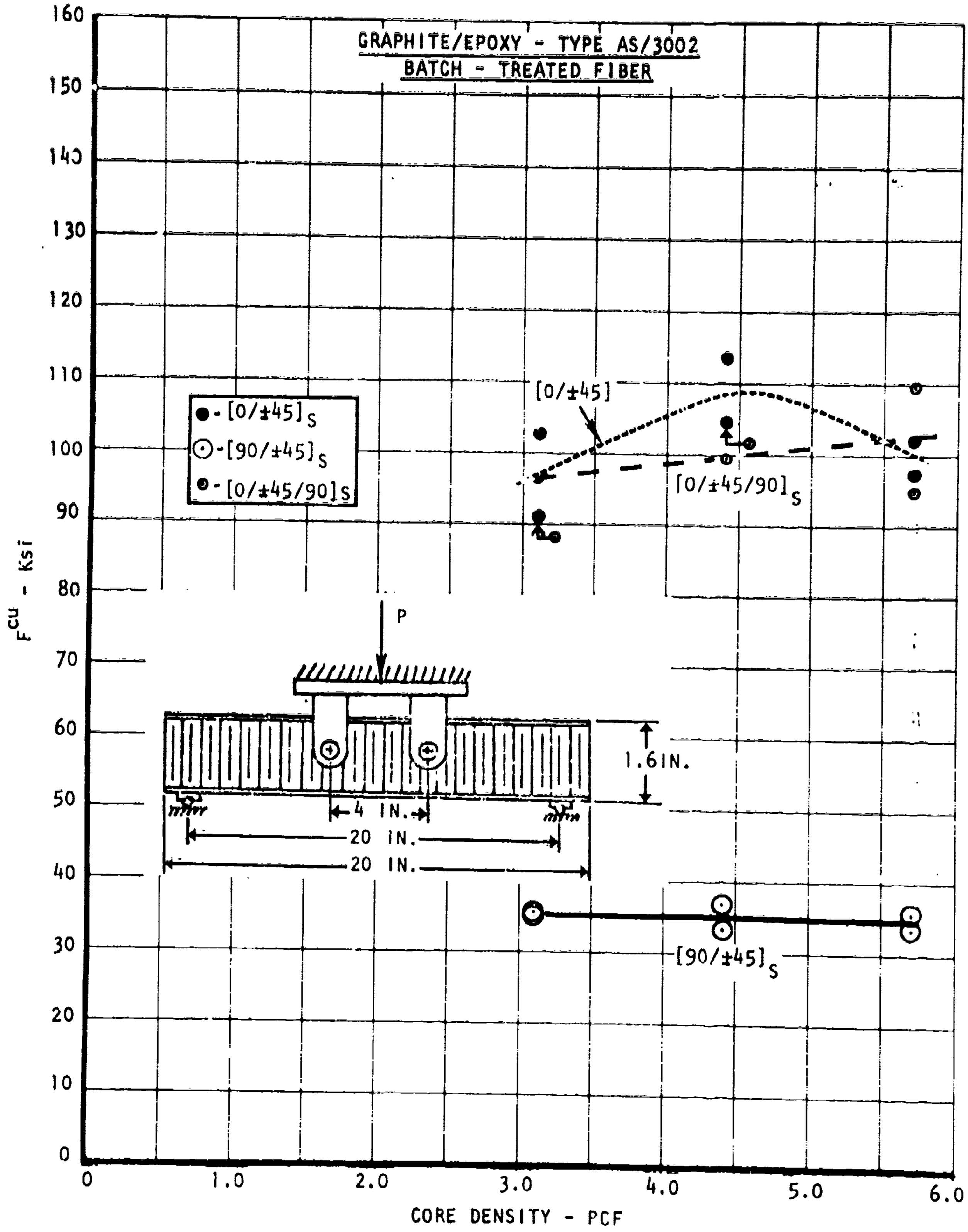


Figure 164. Graphite/Epoxy Sandwich Beam Compression Data - Effect of Core Density and Laminate Orientation - Room Temperature - Secondary Bonded

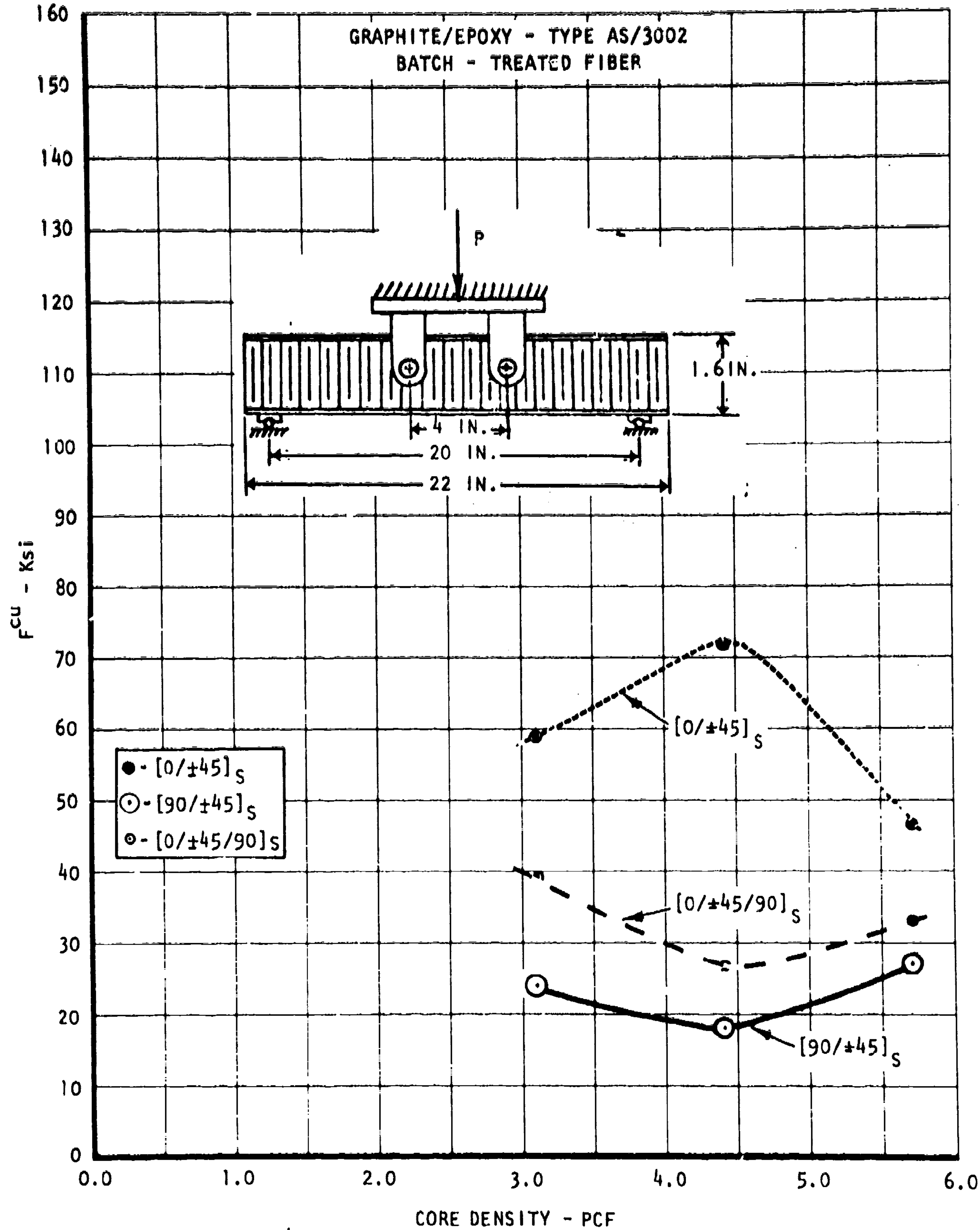


Figure 165. Graphite/Epoxy Sandwich Beam Compression Data - Effect of Core Density and Laminate Orientation, 350° F - Secondary Bonded

TABLE LXIV. GRAPHITE/EPOXY OPEN HOLE TENSION DATA - TYPE AS/3002 BATCH (2D/W = 0.5 NOMINAL)

Orientation	Specimen No.	Thick t (in.)	Width W (in.)	Hole Dia D_1 (in.)	Hole Dia D_2 (in.)	Ultimate Stress Gross (Ksi)	Ultimate Stress Net (Ksi)	Temp (°F)	Basic F_x^{tu}* (Ksi)	K_t NET**	$K_{t\infty}$***	$\frac{K_t \text{ NET}}{K_{t\infty}}$
$[0]_{6T}$	TOH-UL-1	0.035	0.995	0.266	0.272	45.80	99.72	RT				
	TOH-UL-2	0.035	0.998	0.271	0.255	60.84	128.6	RT				
	Avg					(53.32)	(114.2)		160	(1.402)	(6.660)	0.21
	TOH-UL-3	0.033	0.998	0.260	0.265	(46.46)	(98.02)	350	144	(1.469)	(8.210)	0.18
$[\pm45]_{2S}$	TOH-8AL-1	0.046	0.994	0.256	0.260	13.45	27.97	RT				
	TOH-8AL-2	0.048	0.997	0.263	0.250	12.75	26.26	RT				
	TOH-8AL-3	0.049	0.996	0.259	0.272	13.01	27.87					
	Avg					(13.07)	(27.37)		26.3	(0.961)	(2.005)	0.48
	TOH-8AL-4	0.0485	0.998	0.263	0.262	(8.37)	(17.65)	350	12	(0.680)	(1.783)	0.38
$[0/90]_{2S}$	TOH-8BL-1	0.048	0.996	0.250	0.256	23.64	48.04	RT				
	TOH-8BL-2	0.049	0.997	0.258	0.250	20.88	42.57	RT				
	Avg					(22.26)	(45.31)		87	(1.920)	(5.026)	0.38
	TOH-8BL-3	0.051	0.994	0.252	0.250	(24.86)	(50.22)	350	76	(1.513)	(6.472)	0.23
$[0/\pm45/90]_S$	TOH-8L-1	0.049	1.004	0.265	0.247	21.95	44.53	RT				
	TOH-8L-2	0.049	0.997	0.256	0.258	20.57	42.46	RT				
	TOH-8L-3	0.049	0.998	0.256	0.265	16.87	35.30	RT				
	Avg					(19.80)	(40.76)		64	(1.570)	(2.990)	0.53
	TOH-8L-4	0.049	0.997	0.258	0.272	(19.75)	(42.17)	350	54	(1.281)	(3.000)	0.43

*Refer to section V

**Basic F_x^{tu} / Ult Stress (net)

***

$$K_{t\infty} = 1 + \left\{ 2\left[\left(\frac{E_x}{E_y}\right)^{1/2} - \nu_{xy}\right] + \frac{E_x}{G_{xy}} \right\}^{1/2}$$

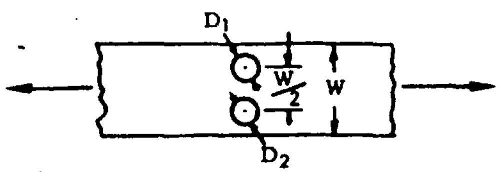


TABLE LXV. GRAPHITE/EPOXY OPEN HOLE TENSION DATA - TYPE AS/3002 BATCH (2D/W = 0.5 NOMINAL)

Orientation	Specimen No.	Thick t (in.)	Width W (in.)	Hole Dia D_1 (in.)	Hole Dia D_2 (in.)	Ultimate Stress Gross (Ksi)	Ultimate Stress Net (Ksi)	Temp (°F)	Basic F_x^{tu}* (Ksi)	K_t NET**	$K_{t\infty}$***	$\frac{K_t\ NET}{K_{t\infty}}$
$[0/\pm45]_S$	TOH-6L-1	0.037	1.001	0.259	0.269	26.46	56.00	RT				
	TOH-6L-2	0.0365	0.996	0.254	0.256	22.79	47.35	RT				
	TOH-6L-3	0.035	0.995	0.261	0.264	22.83	48.33	RT				
	Avg					(24.03)	(50.56)		70	(1.384)	(2.960)	0.47
	TOH-6L-4	0.037	0.998	0.258	0.257	(27.62)	(57.08)	350	57	(0.999)	(2.930)	0.34
$[90/\pm45]_S$	TOH-6T-1	0.037	1.003	0.269	0.270	11.67	25.22	RT				
	TOH-6T-2	0.037	1.001	0.257	0.259	11.29	23.29	RT				
	TOH-6T-3	0.0355	1.001	0.260	0.259	13.79	28.64	RT				
	Avg					(12.25)	(25.72)		26	(1.011)	(2.353)	0.43
	TOH-6T-4	0.037	0.999	0.261	0.261	(7.25)	(15.18)	350	20	(1.318)	(2.250)	0.59
$[0_2/\pm45]_S$	TOH-8CL-1	0.049	0.998	0.270	0.269	46.73	101.60	RT				
	TOH-8CL-2	0.050	1.000	0.255	0.256	45.00	92.03	RT				
	TOH-8CL-3	0.048	0.999	0.273	0.273	44.84	98.88	RT				
	Avg					(45.52)	(97.50)		93	(0.954)	(3.440)	0.28
	TOH-8CL-4	0.049	0.995	0.266	0.265	(39.28)	(84.23)	350	80	(0.950)	(3.533)	0.27
$[90_2/\pm45]_S$	TOH-8CT-1	0.049	0.998	0.265	0.264	10.45	22.24	RT				
	TOH-8CT-2	0.045	0.995	0.267	0.265	9.11	19.58	RT				
	TOH-8CT-3	0.049	0.990	0.241	0.254	10.33	20.66	RT				
	Avg					(9.96)	(20.83)		24	(1.152)	(2.009)	0.57
	TOH-8CT-4	0.050	0.999	0.270	0.259	(7.81)	(16.60)	350	19	(1.145)	(2.292)	0.50

*Refer to section V

**Basic F_x^{tu} / Ultimate Stress (net)

***

$$K_{t\infty} = 1 + \left\{ 2 \left[\left(\frac{E_x}{E_y} \right)^{1/2} - \nu_{xy} \right] + \frac{E_x}{G_{xy}} \right\}^{1/2}$$

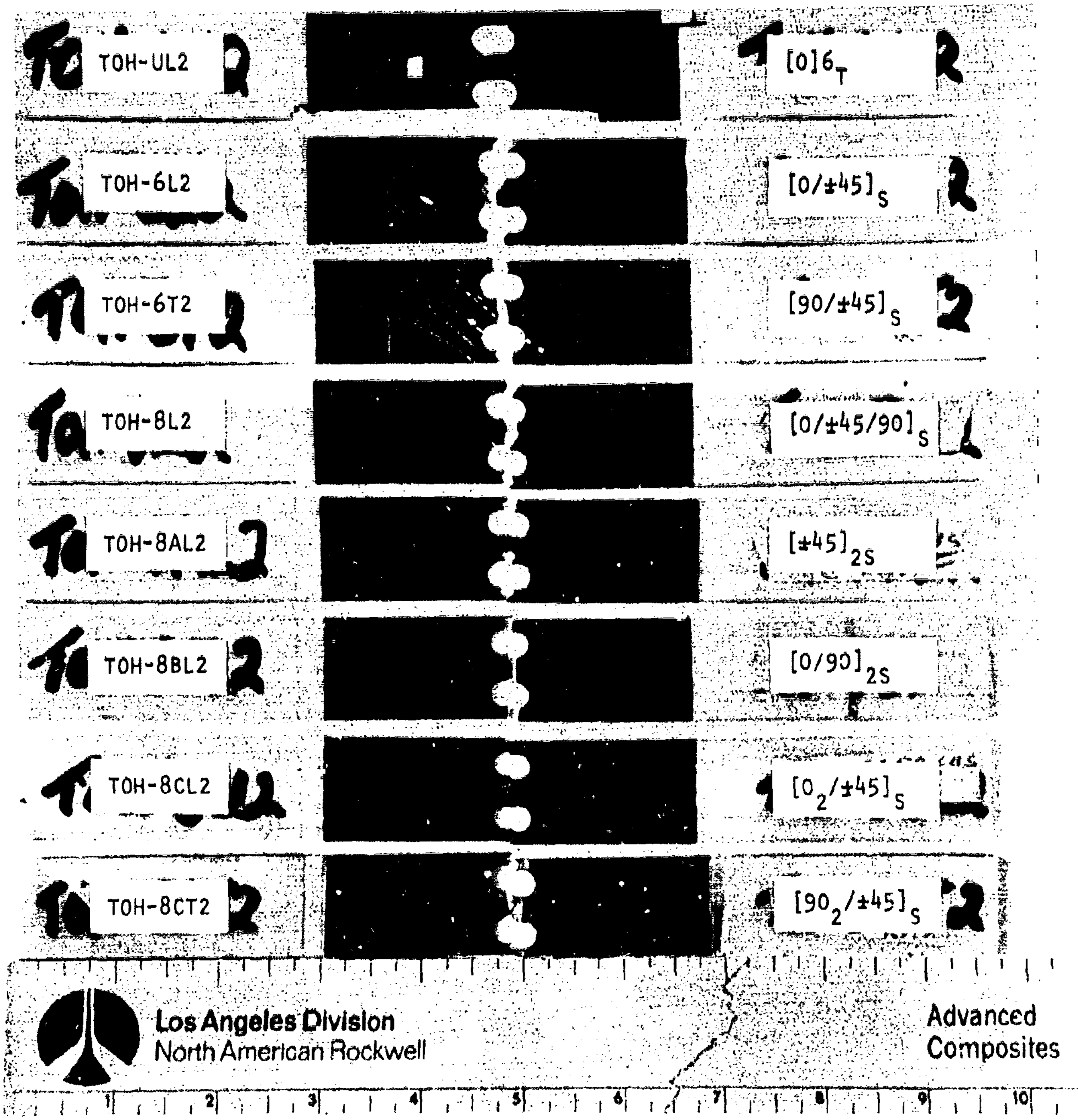


Figure 166. Typical Failed Open Hole Graphite/Epoxy Specimens - Room Temperature, 2D/W = 0.50, Type AS/3002 Batch

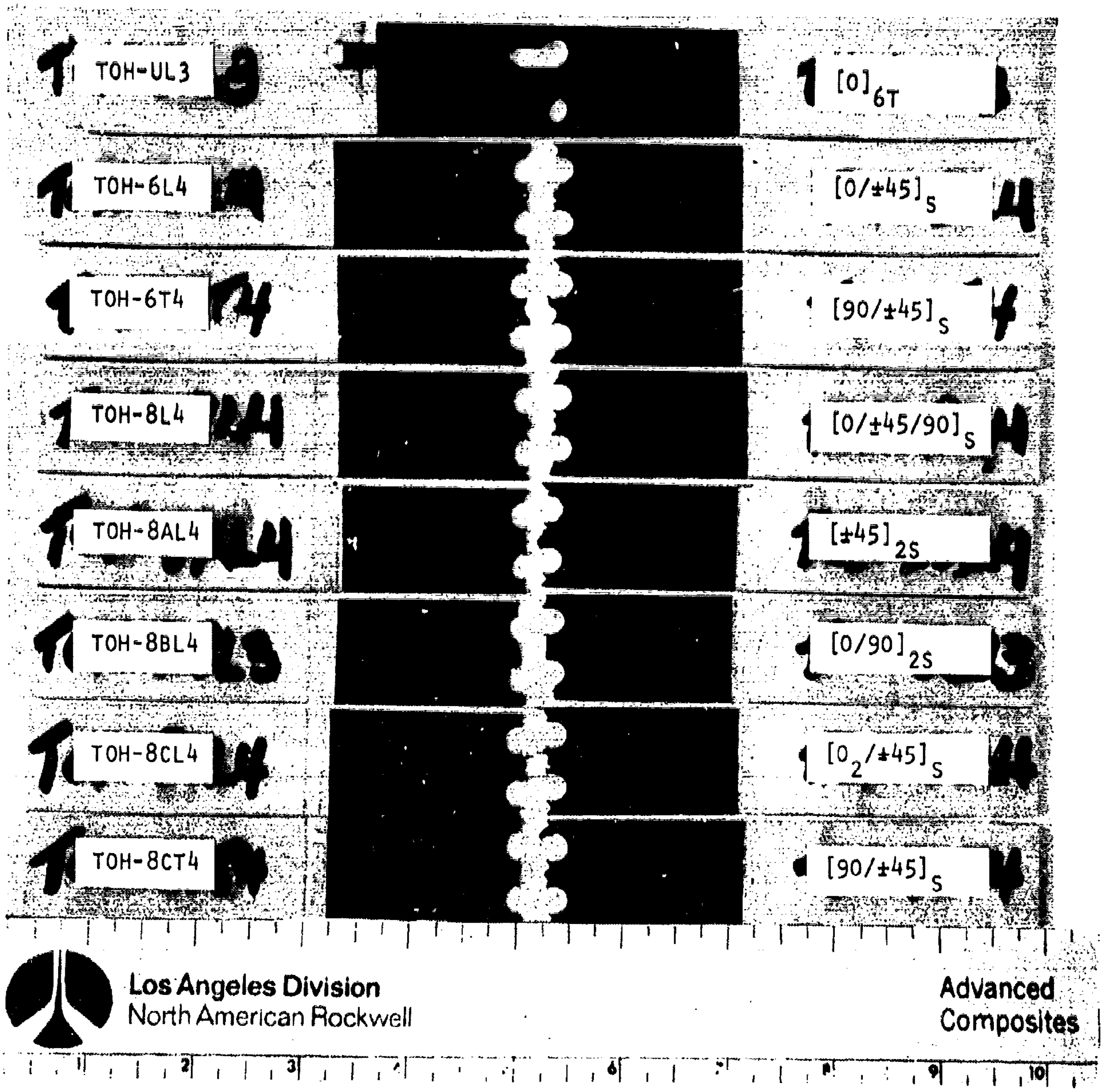


Figure 167. Typical Failed Open Hole Graphite/Epoxy Specimens - 350° F, 2D/W = 0.50, Type AS/3002 Batch

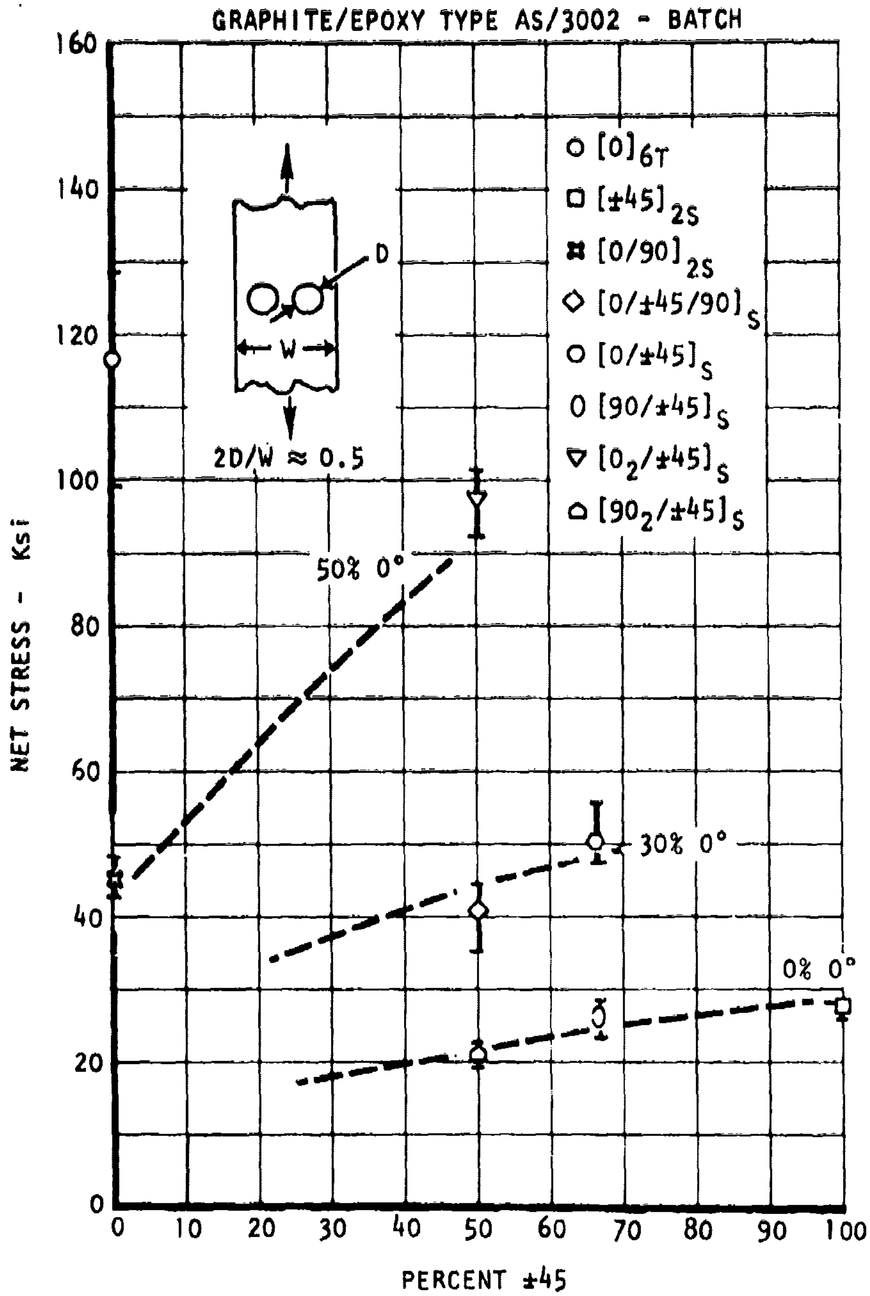


Figure 168. Effect of Laminate Orientation on Net Tension Strength of Laminates With Open Holes - Room Temperature

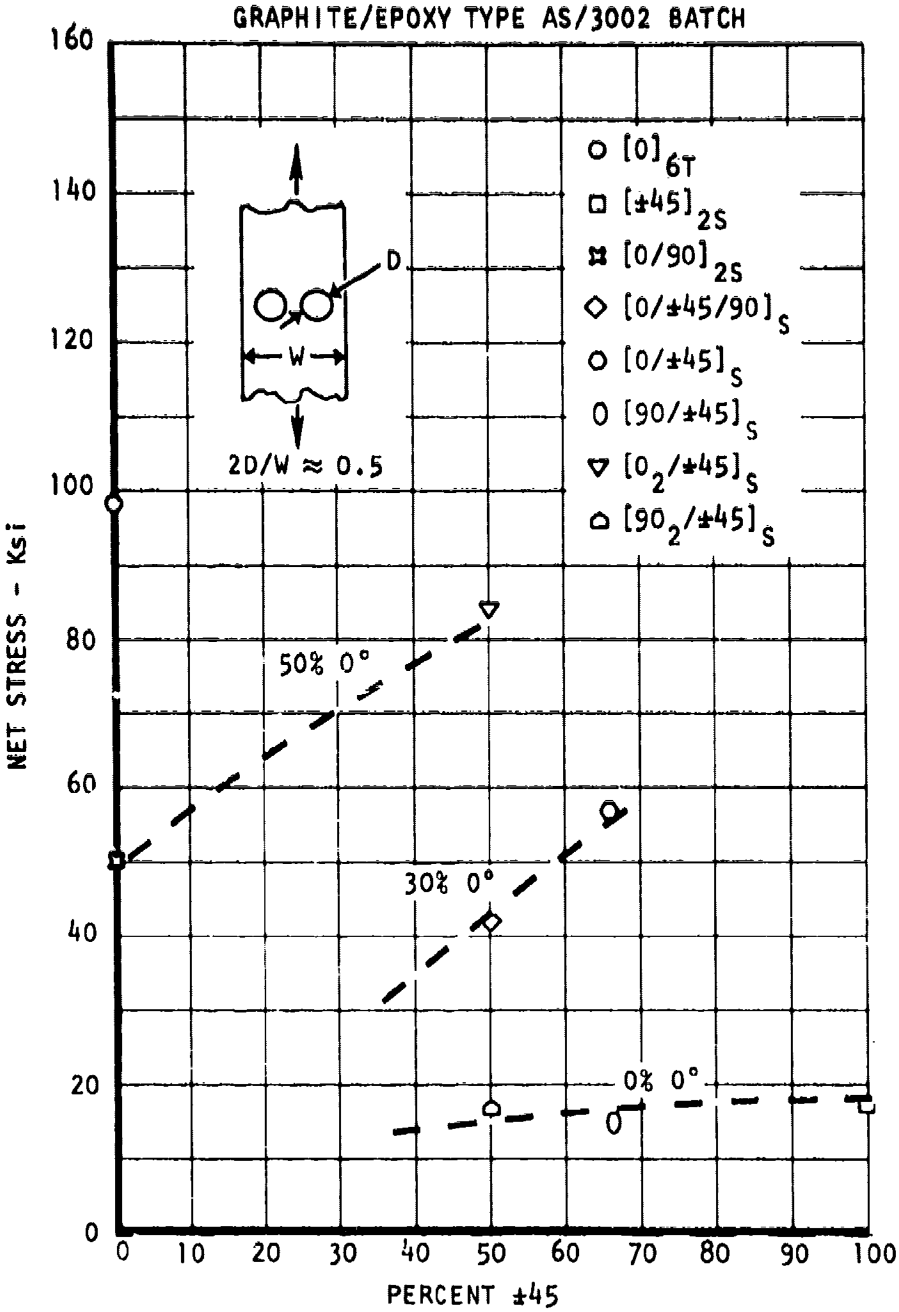


Figure 169. Effect of Laminate Orientation on Net Tension Strength of Laminates With Open Holes, 350° F

orientations tested with the various stress concentration factors at room temperature ranging from 0.95 for $[\pm45]_{2S}$ to 1.57 for $[0/\pm45/90]_S$ with an average K_t net of 1.29 for the various laminate orientations tested (2D/W = 0.5). Furthermore, at 350°F, K_t net ranged from 0.68 for $[\pm45]_{2S}$ to 1.47 for $[0]_{6T}$ with an average k_t net of 1.17 for the various orientations tested. It should be noted that a K_t net value less than unity such as that for the $[\pm45]_{2S}$ at 350°F is not realistic and indicates a probable basic lower than average test value for the "no hole" value.

Tables LXIV and LXV also have a column where the test values of K_t net are compared to $K_{t\infty}$, theoretical elastic stress concentration factor for an infinitely wide panel (reference 1). The ratio of K_t (net)/$K_{t\infty}$ is a measure of the stress reduction effects at ultimate load compared with the theoretical elastic stress concentration effects. The ratios obtained for the various laminates (all D/W = 0.5) averaged about 0.39 which is in fairly good agreement with the 0.50 value obtained in chapter 6 of reference 1 for various graphite/epoxy orientations and D/W ratios. The values less than unity show that there is a redistribution of stresses in the laminates at ultimate load to effectively reduce the elastic stress concentration factor.

Compression Loaded Open Holes

Table LXVI summarizes the test data for the graphite/epoxy open hole compression sandwich bending beam specimens. Both undirectional and crossplied orientations were tested, with both room and 350°F temperature tests being run. The failure mode for the unidirectional specimens was an adhesive failure between the face sheets and core, while the crossplied beams failed in compression at the holes in the graphite/epoxy face sheet. Typical failed specimens are shown in figures 170 through 173.

The $[0]_{6T}$ open hole compression strengths (NET) were 12 percent and 6 percent less than the strength of specimens without holes, at room temperature and 350°F respectively. These values are not conclusive, however, since the failures were core to face sheet adhesive failure rather than face sheet compression failures.

The room temperature open hole tests for the three crossplied laminates tested were 25 to 51 percent lower than the basic F_x^{cu}. The lower than basic F_x^{cu} values indicate the presence of a stress concentration at the hole. The 350°F crossplied open hole compression strengths (NET) were 6 to 25 percent lower than the basic F_x^{cu}.

Figures 174 and 175 show plots of net stress versus percent of ±45° plies, for room temperature and 350°F, respectively. The curves are of the expected form, with lower strengths at higher percentages of ±45° plies and lower percentage of 0° plies.

Comparison of compression open hole data with tension open hole data shows that the stress concentrations are generally equivalent for the comparable laminate orientations tested, the notable exception being the [±45] orientation which exhibited no tension notch sensitivity but has 15 to 25 percent strength degradations in compression.

TABLE LXVI. GRAPHITE/EPOXY OPEN HOLE COMPRESSION SANDWICH BENDING BEAM DATA - TYPE AS/3002 BATCH (D/W = 0.5 NOMINAL)

Orientation	Specimen No.	Thick t (in.)	Width W (in.)	Hole Dia D (in.)	Ultimate Stress		Temp (°F)	Basic F_x^{cu} (Ksi)	Net Stress / Basic F_x^{cu}	Failure Mode**
					Gross (Ksi)	Net (Ksi)				
$[0]_{6T}$	COH-UL-1	0.036	0.983	0.508	(72.55)	(150.14)	RT	171.09	(0.88)	A
	COH-UL-2	0.036	0.989	0.507	(31.37)	(64.36)	350	68.37	(0.94)	A
$[\pm 45]_{2S}$	COH-8AL-2	0.048	0.989	0.506	30.71	62.88	RT			C
	COH-8AL-3	0.048	0.990	0.507	21.80	44.68	RT			C
	COH-8AL-4	0.048	0.973	0.507	16.70	34.87	RT			C
	Avg				(23.07)	(47.48)		63.0*	(0.75)	
	COH-8AL-1	0.048	0.964	0.504	(8.29)	(17.38)	350	20.5*	(0.85)	C
$[0/\pm 45]_S$	COH-6L-1	0.036	0.985	0.508	31.86	65.78	RT			C
	COH-6L-2	0.036	0.997	0.505	24.68	50.01	RT			C
	COH-6L-3	0.036	0.981	0.506	41.44	85.58	RT			C
	Avg				(32.66)	(67.12)		116.87	(0.57)	
	COH-6L-4	0.036	0.979	0.506	(27.69)	(57.30)	350	60.94	(0.94)	C
$[0/\pm 45/90]_S$	COH-8L-1	0.048	0.971	0.505	18.66	38.88	RT			C
	COH-8L-2	0.048	0.980	0.508	19.85	41.20	RT			C
	COH-8L-3	0.048	0.974	0.506	28.72	59.77	RT			C
	Avg				(22.41)	(46.62)		95.96	(0.49)	
	COH-8L-4	0.048	0.987	0.507	(22.13)	(45.51)	350	60.42	(0.75)	C

*Basic F_x^{cu} is an estimated compression ultimate value, all other basic F_x^{cu} values from compression beam tests without holes in face sheets.

**A = Adhesive failure away from hole; C = Facesheet compression failure at hole

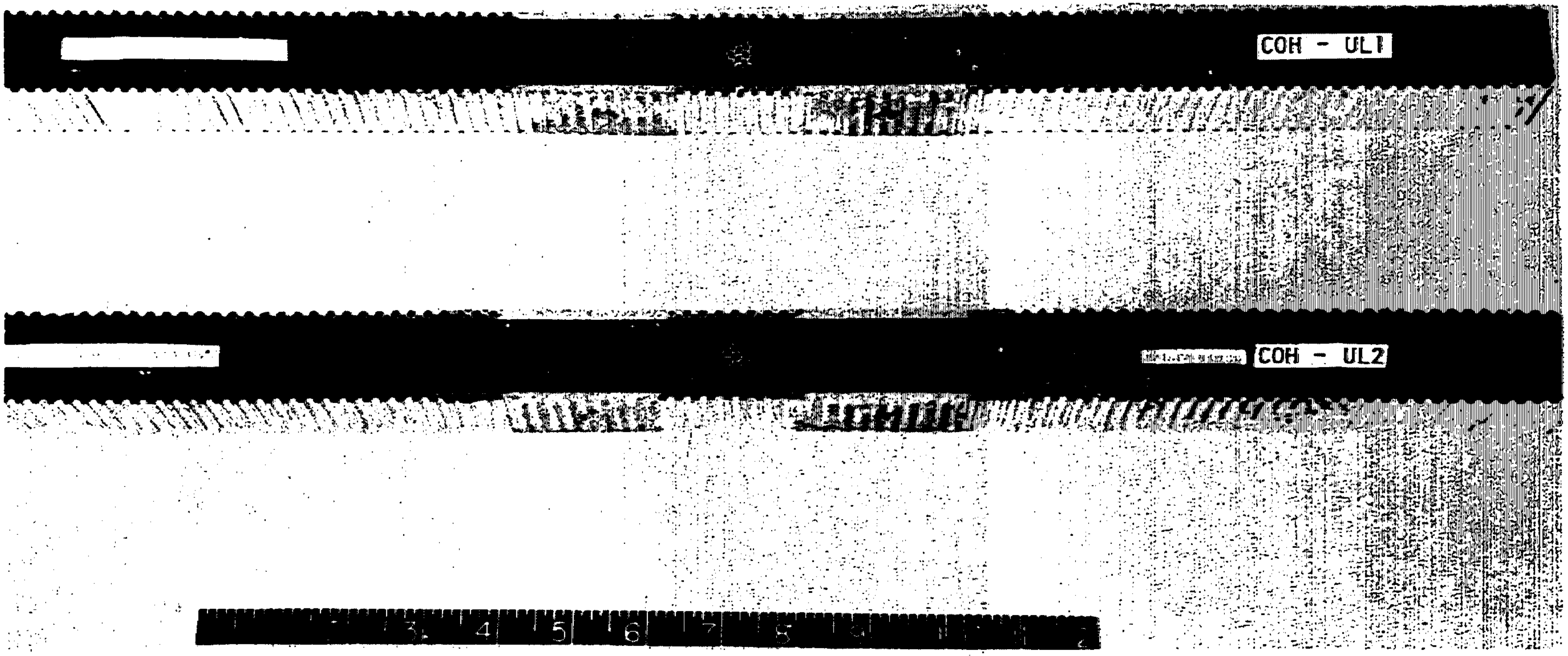


Figure 170. Failed $[0]_{6T}$ Open Hole Compression Bending Beams - Type AS/3002 Batch Graphite/Epoxy

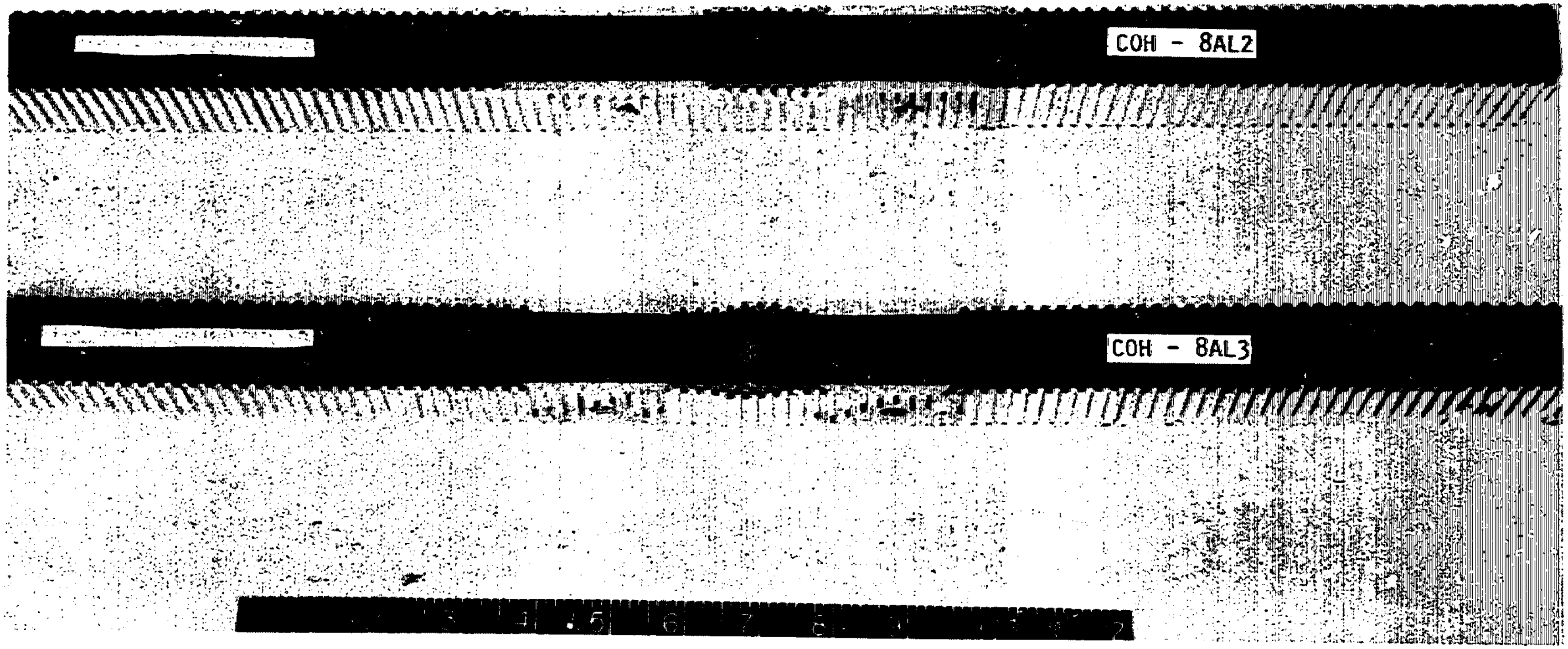


Figure 171. Failed $[\pm 45]_{2S}$ Open Hole Compression Bending Beams - Type AS/3002 Batch Graphite/Epoxy

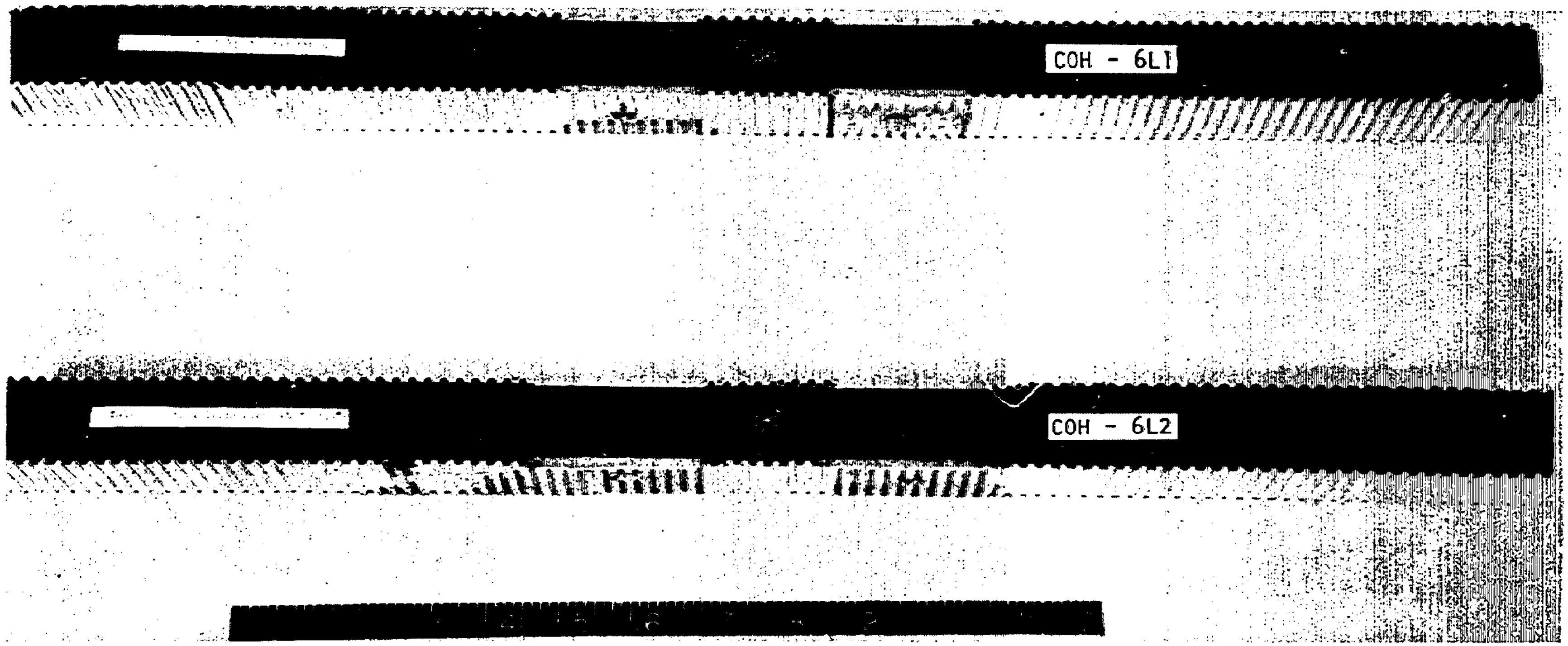


Figure 172. Failed $[0/\pm45]_S$ Open Hole Compression Bending Beams - Type AS/3002 Batch Graphite/Epoxy

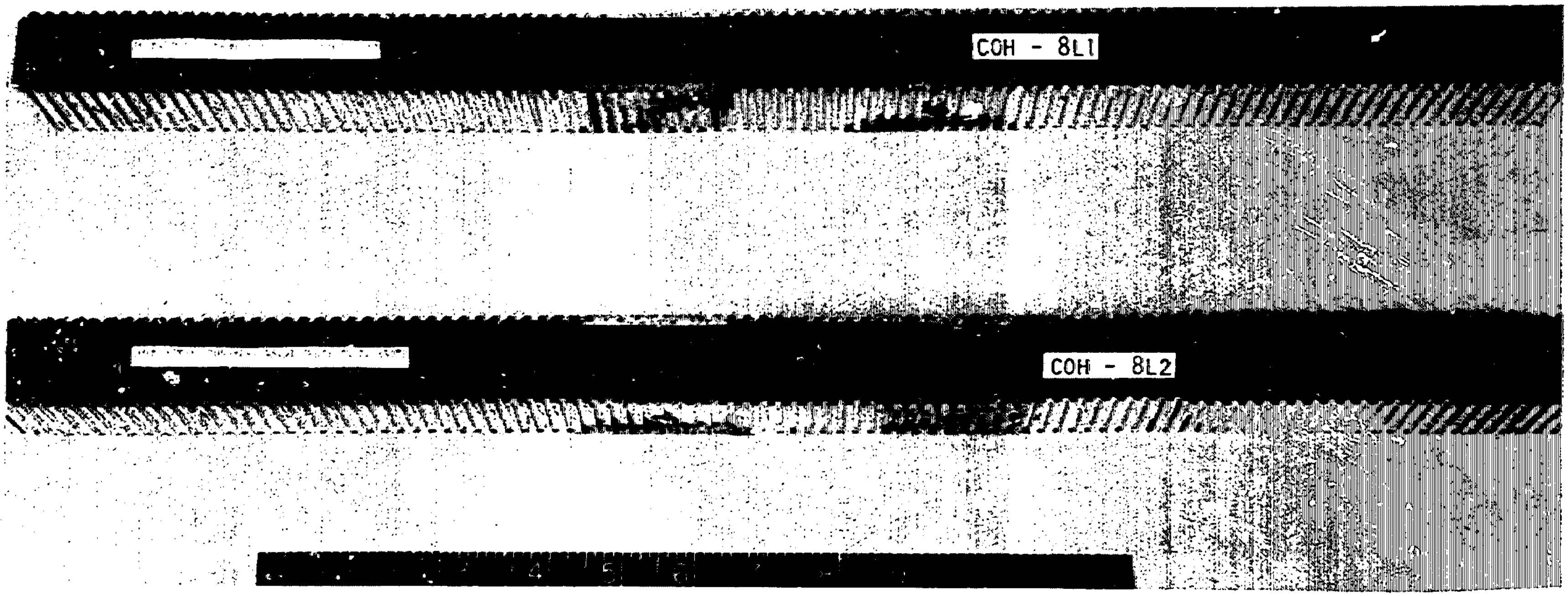


Figure 173. Failed $[0/\pm 45/90]_S$ Open Hole Compression Bending Beams - Type AS/3002 Batch Graphite/Epoxy

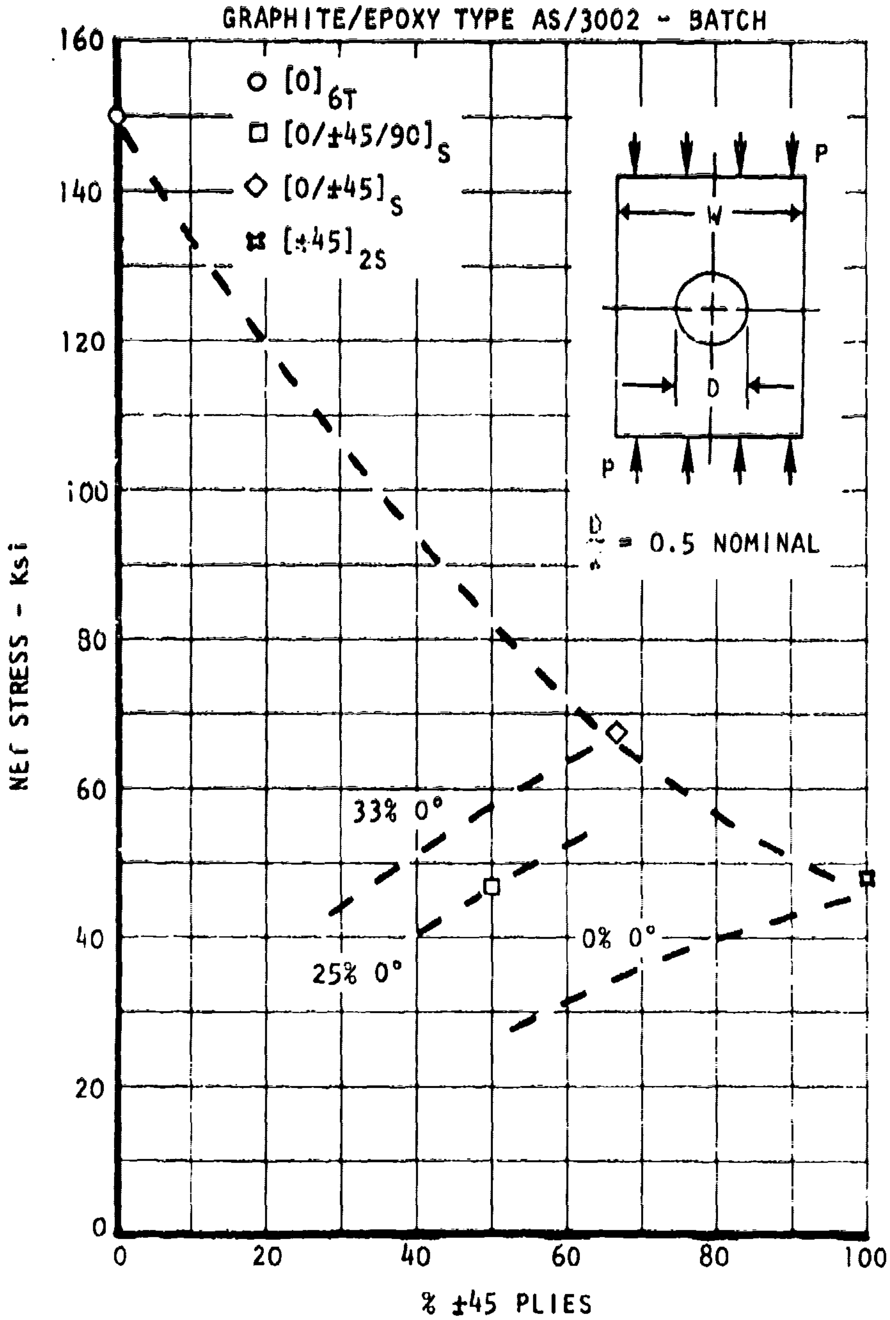


Figure 174 Effect of Laminate Orientation on Net Compression Strength of Laminates With Open Holes - Room Temperature

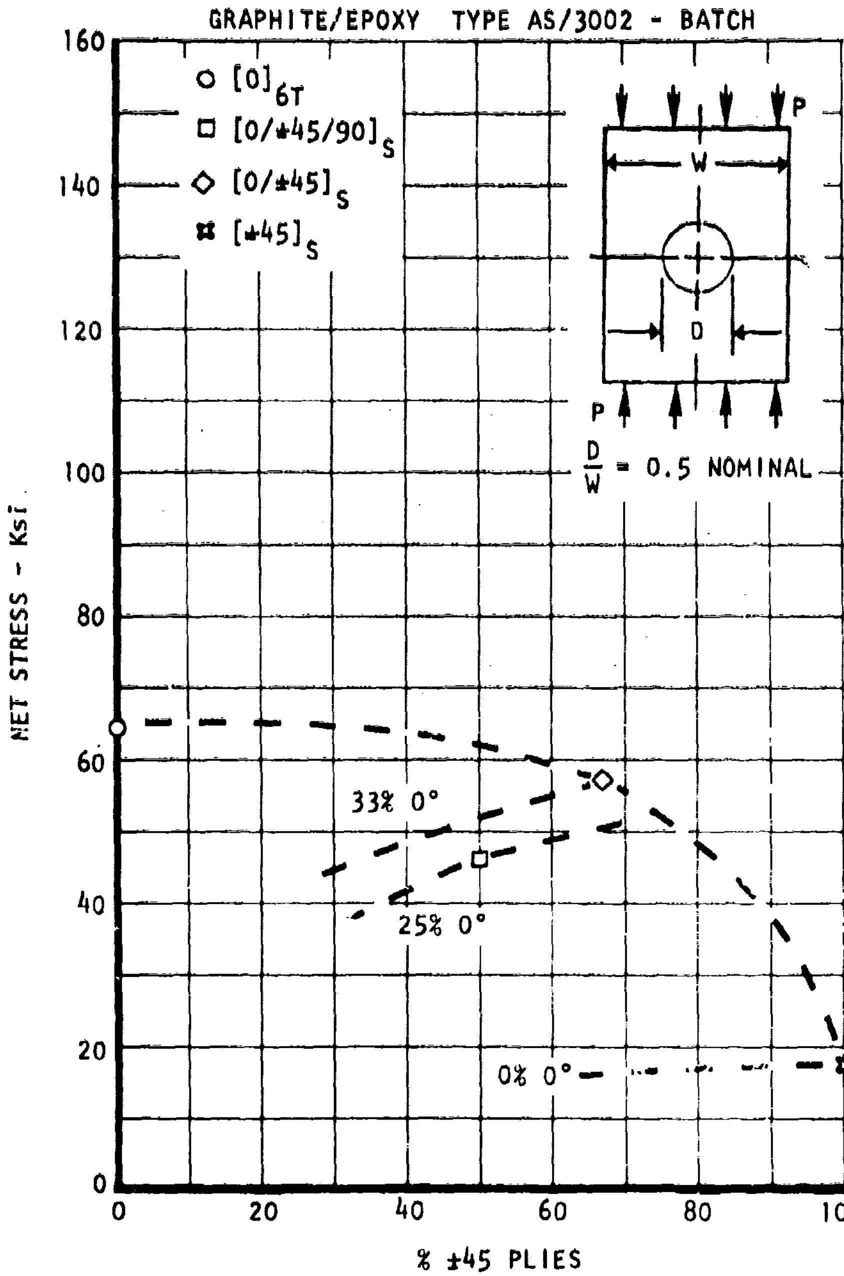


Figure 175. Effect of Laminate Orientation on Net Compression Strength of Laminates With Open Holes, 350° F

THICKNESS BUILDUP TENSION TESTS

Room temperature thickness buildup tension coupon data are summarized in table LXVII. Basic orientations of $[0/\pm45/90]_S$, $[0/\pm45]_S$, and $[0_2/\pm45/90]_S$ with buildups of 1.5, 2, and 3 t were tested. Also, photographs of typical failed specimens are shown in figures 176, 177, and 178. Furthermore, a plot of back-to-back strain gage data for the three crossplied orientations are shown in figure 179. These stress-strain curves show that little or no bending was present at this location because of the thickness buildup. As a point of interest, a plot of test stress versus predicted strain gage stress is presented in figure 180 and shows very good correlation. The test stresses were based on the test load/specimen cross-sectional area. The predicted stresses were based on the strain gage data and crossplied laminate elastic constants from section V.

An examination of table LXVII and figure 181 shows that there was a 20- to 25- percent average reduction in ultimate tensile strength due to thickness buildup, with the only exceptions being for the $[0_2/\pm45]_S$ laminate with thickness buildup factors of 2 and 3. The lowering in ultimate tensile strength was from some unexplained source. A fabrication problem possibly exists, as an examination of the failed specimens showed that all the failures occurred well away from the thickness builup area, hence indicating that there was little stress concentration introduced by the buildup.

TABLE LXVII. CROSSPLIED THICKNESS BUILDUP SPECIMEN DATA - TYPE AS/3002 BATCH GRAPHITE/EPOXY - ROOM TEMPERATURE

Orientation	Specimen No.	Width (in.)	Test Section Thickness (in.)	Buildup Thickness (in.)	Ultimate Test Section Stress (Ksi)	Average	Test/Predicted Stress*
$[0/\pm45]_S$	TTB-6L 1.5T1	1.875	0.036	0.054	61.48		0.88
	TTB-6L 1.5T2	1.722	0.036	0.050	54.60	(55.55)	0.78 (0.79)
	TTB-6L 1.5T3	1.904	0.036	0.049	59.58		0.72
	TTB-6L 2T1	1.866	0.038	0.074	49.86		0.71
	TTB-6L 2T2	1.873	0.037	0.076	49.06	(50.92)	0.70 (0.73)
	TTB-6L 2T3	1.766	0.036	0.074	53.85		0.77
	TTB-6L 3T1	1.876	0.036	0.102**	51.33		0.73
	TTB-6L 3T2	1.885	0.037	0.102**	59.31	(54.39)	0.85 (0.78)
	TTB-6L 3T3	1.874	0.038	0.102**	52.53		0.75
$[0/\pm45/90]_S$	TTB-8L 1.5T1	1.828	0.050	0.074	52.19		0.82
	TTB-8L 1.5T2	1.887	0.050	0.075	51.91	(49.95)	0.81 (0.78)
	TTB-8L 1.5T3	1.887	0.050	0.075	45.75		0.72
	TTB-8L 2T1	1.864	0.050	0.099	56.17		0.88
	TTB-8L 2T2	1.866	0.046	0.098	43.10	(53.80)	0.67 (0.84)
	TTB-8L 2T3	1.873	0.052	0.093	62.12		0.97
	TTB-8L 3T1	1.842	0.050	0.149**	60.80		0.95
	TTB-8L 3T2	1.842	0.053	0.149**	54.25	(58.37)	0.85 (0.91)
	TTB-8L 3T3	1.848	0.050	0.149**	60.07		0.94

TABLE LXVII. CROSSPLIED THICKNESS BUILDUP SPECIMEN DATA - TYPE AS/3002 BATCH GRAPHITE/EPOXY - ROOM TEMPERATURE (CONCLUDED)

Orientation	Specimen No.	Width (in.)	Test Section Thickness (in.)	Buildup Thickness (in.)	Ultimate Test Section Stress (Ksi)	Average	Test/Predicted Stress*	
$[0_2/\pm45]_S$	TTB-8CL 1.5T1	1.872	0.047	0.076	80.06		0.86	
	TTB-8CL 1.5T2	1.860	0.048	0.071	73.46	(75.99)	0.79	(0.82)
	TTB-8CL 1.5T3	1.907	0.051	0.070	74.46		0.80	
	TTB-8CL 2T1	1.736	0.047	0.099	104.17		1.12	
	TTB-8CL 2T2	1.859	0.049	0.099	108.46	(104.75)	1.17	(1.13)
	TTB-8CL 2T3	1.854	0.047	0.105	101.61		1.09	
	TTB-8CL 3T1	1.866	0.052	0.145**	94.02		1.01	
	TTB-8CL 3T2	1.882	0.050	0.145**	111.80	(102.98)	1.20	(1.11)
	TTB-8CL 3T3	1.881	0.046	0.145**	103.12		1.11	

*Predicted ultimate stress for flat coupon with no thickness buildup.
**Estimated thickness.

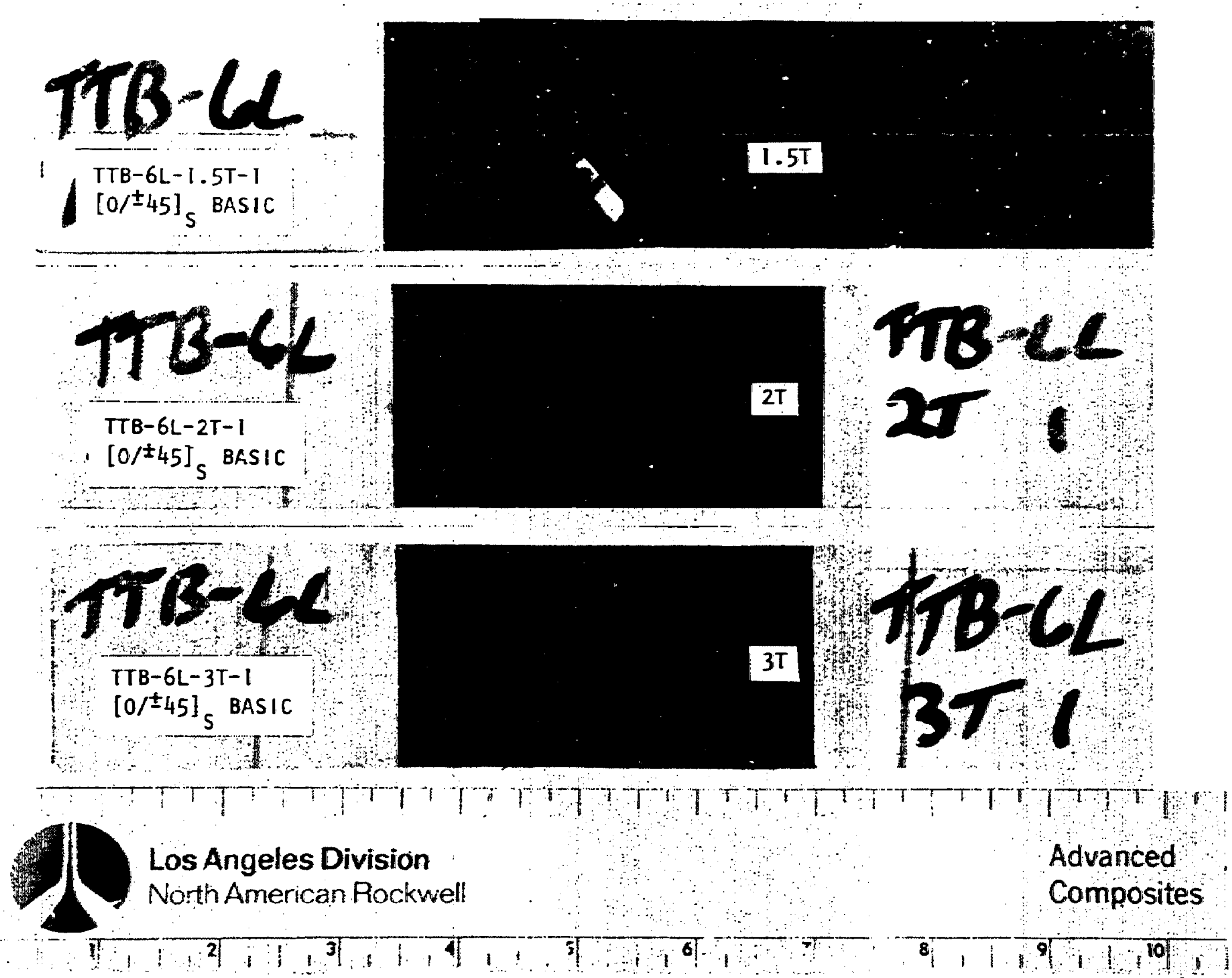


Figure 176. Typical Failed Thickness Buildup Specimens - Graphite/Epoxy, Room Temperature, $[0/\pm 45]_S$ Basic, 1.5t, 2t, and 3t, Type AS/3002 Batch

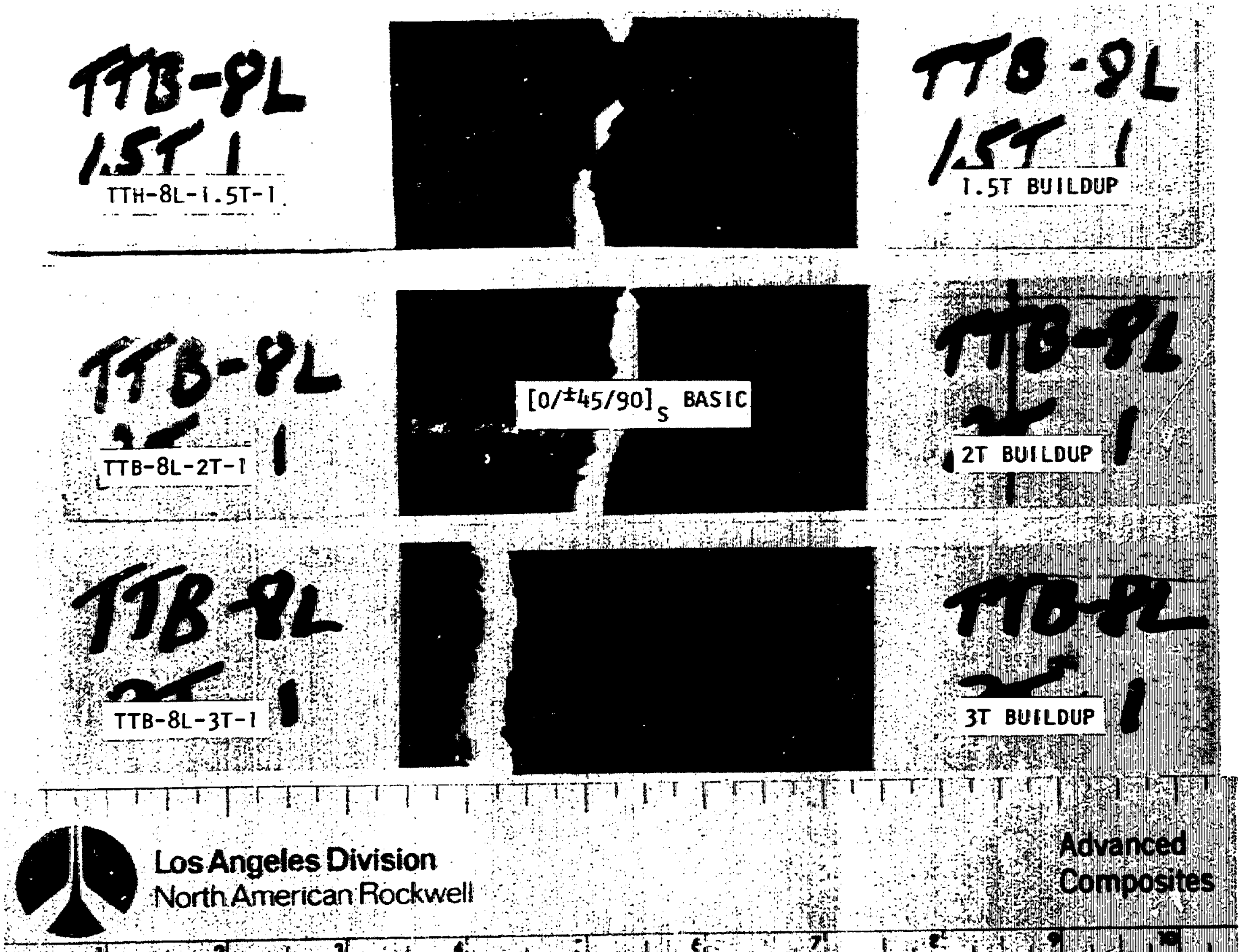


Figure 177. Typical Failed Thickness Buildup Graphite/Epoxy Specimens - Room Temperature, $[0/\pm45/90]_S$ Basic, 1.5t, 2t, and 3t, Type AS/3002 Batch

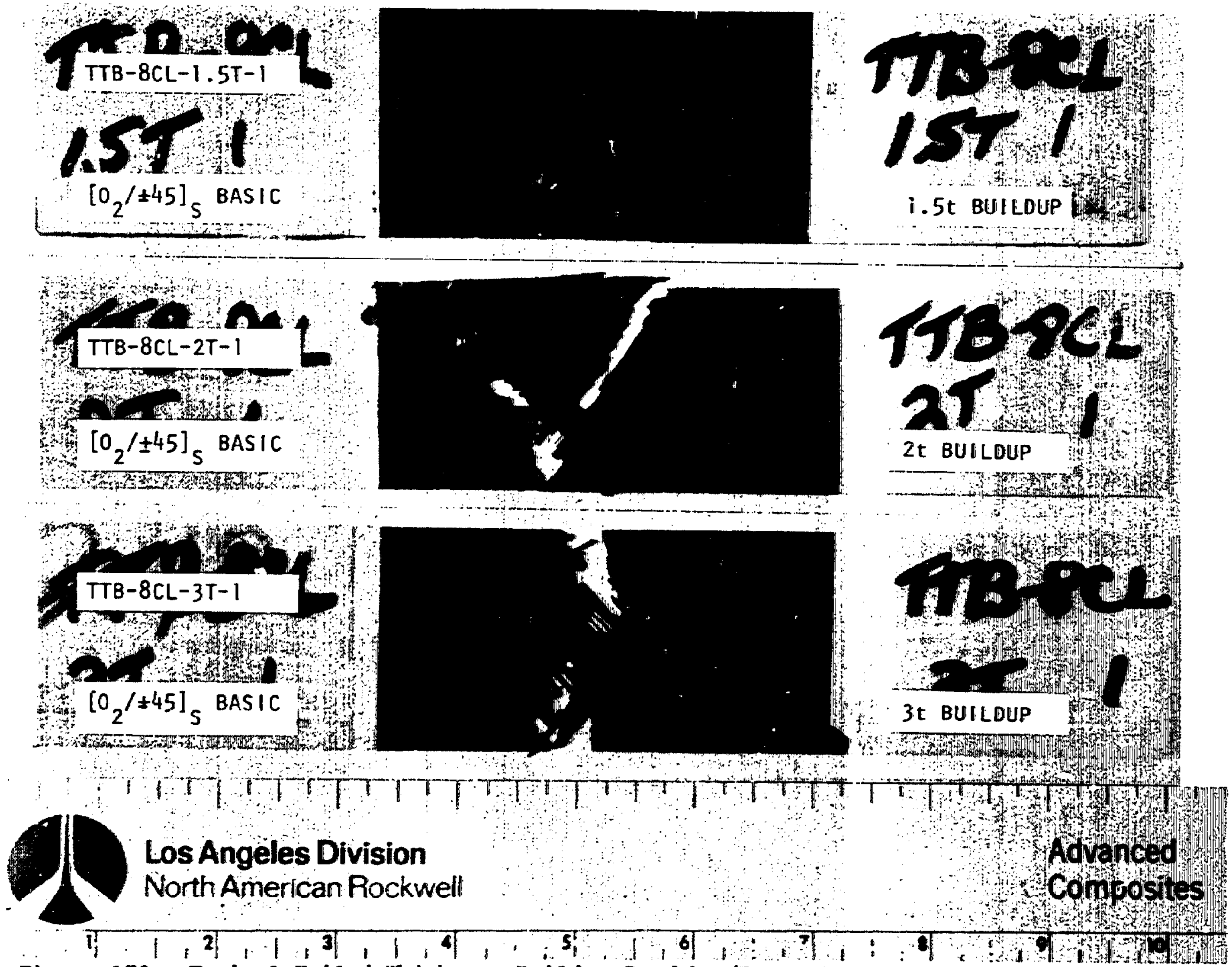


Figure 178. Typical Failed Thickness Buildup Graphite/Epoxy Specimens - Room Temperature, $[0_2/\pm45]_S$ Basic, 1.5t, 2t, and 3t, Type AS/3002 Batch

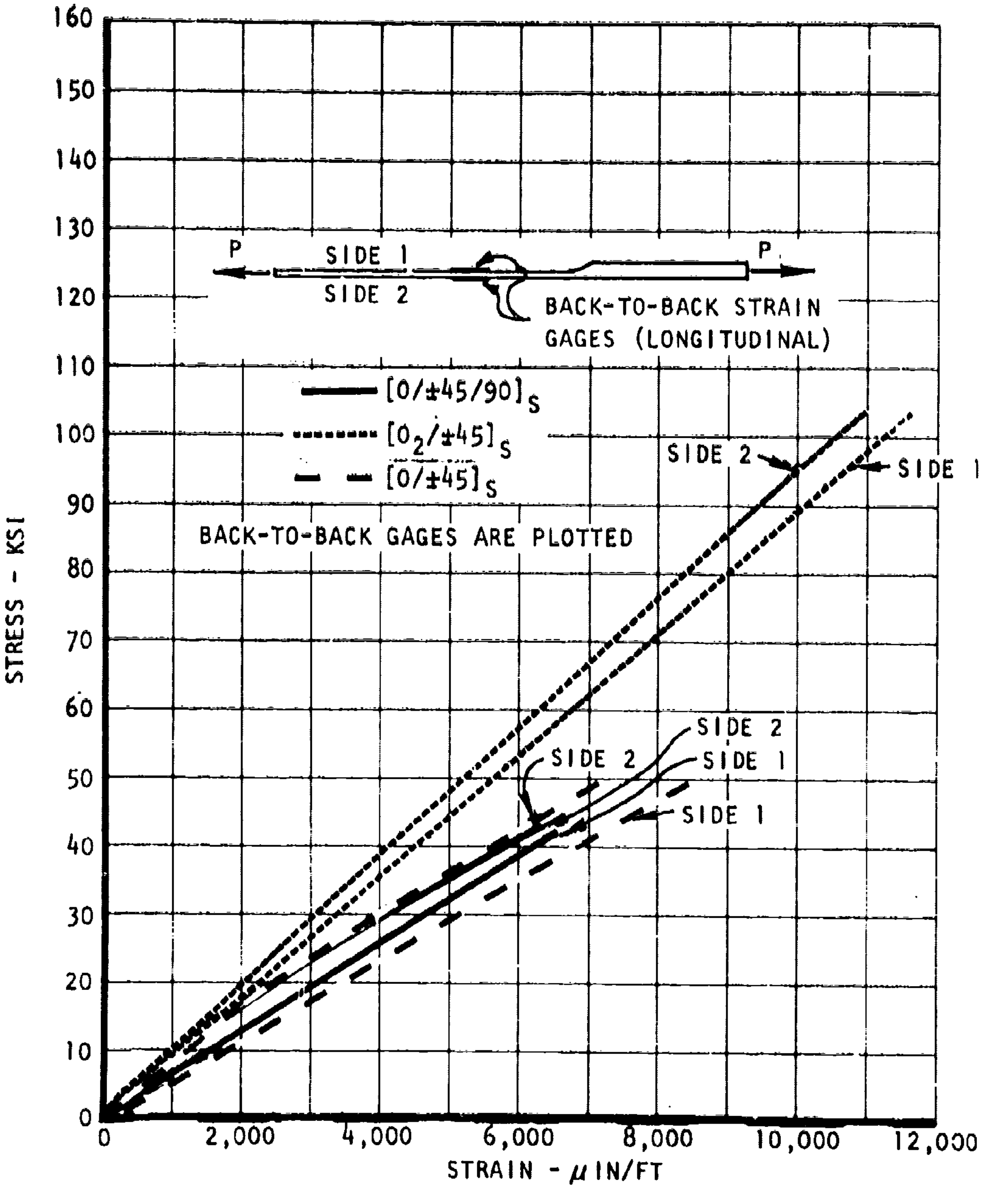


Figure 179. Stress-Strain Curves for Thickness Buildup Specimens - Type AS/3002 Batch Graphite/Epoxy, Room Temperature

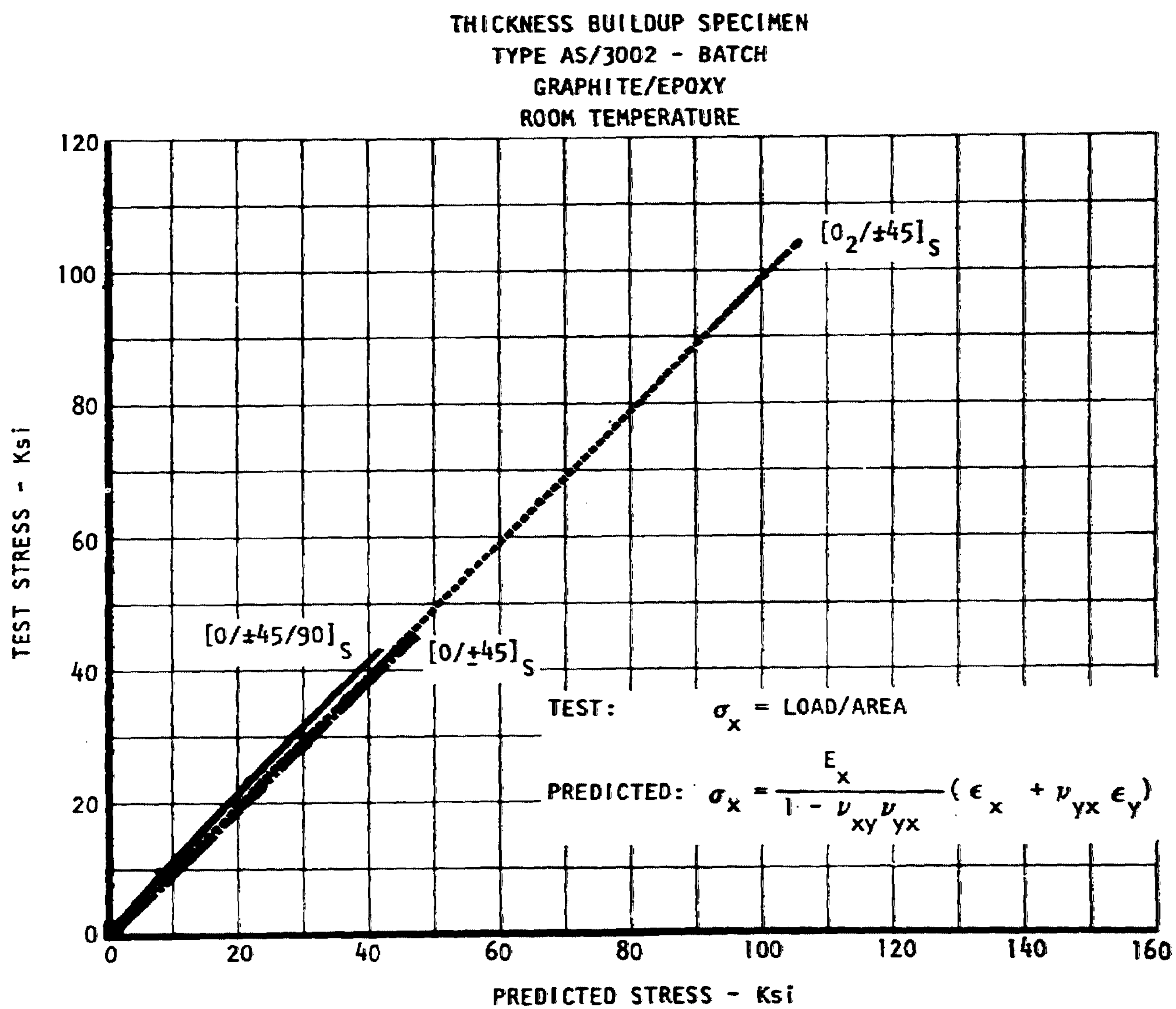


Figure 180. Thickness Buildup Specimens - Graphite/Epoxy Type AS/3002 Batch, at Room Temperature, Strain Gage Predicted Versus P/A Test Stress

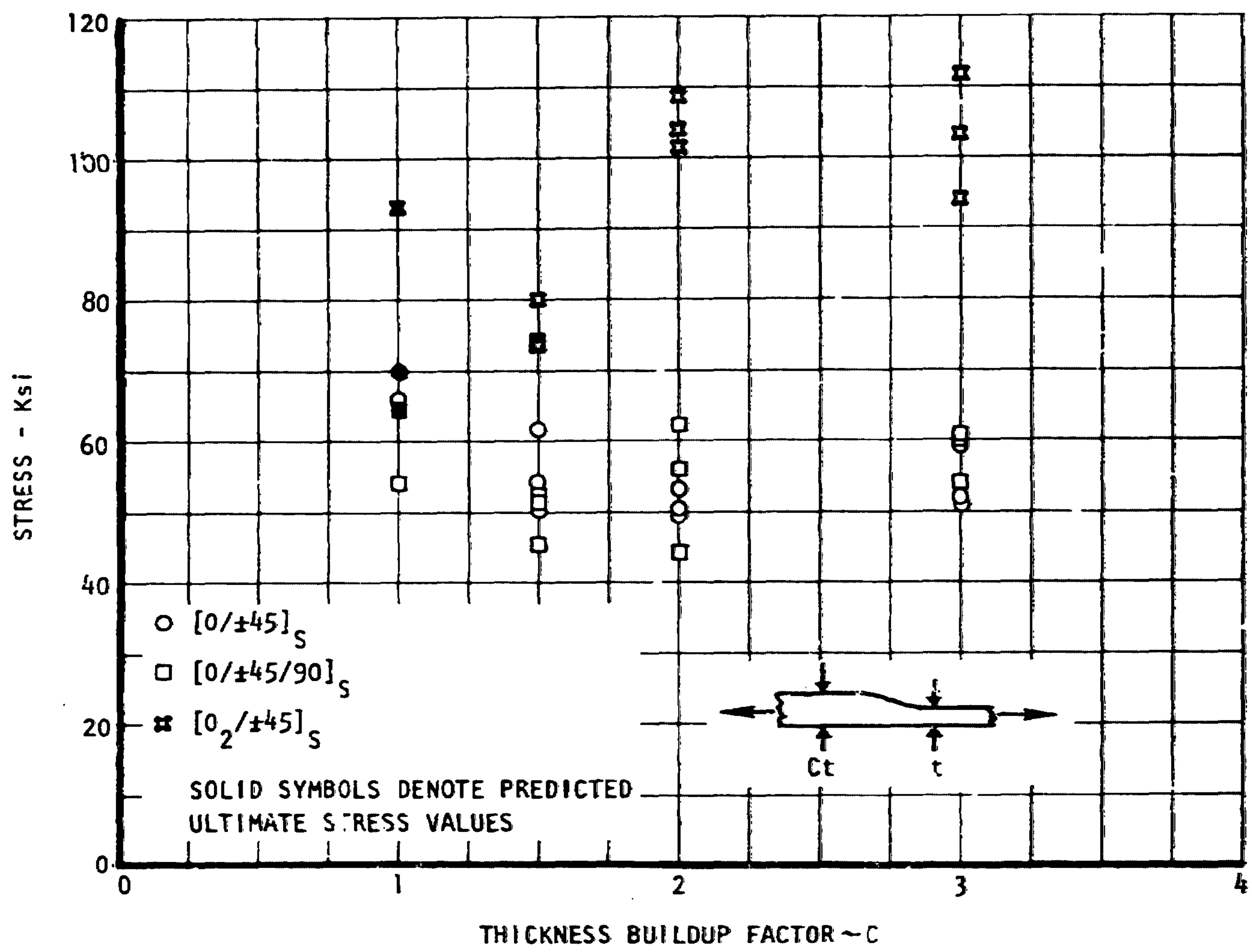


Figure 181. Crossplied Thickness Buildup Specimen Data - Type AS/3002 Batch, Graphite/Epoxy, Various Orientations at Room Temperature

ENVIRONMENTAL EFFECTS

THERMAL CYCLING

Effects on Unidirectional Q.C. Properties

Table LXVIII presents room temperature and 270°F longitudinal and transverse flexure strengths, as well as interlaminar shear strengths, for previously thermal cycled Type AS/3002 - batch unidirectional laminates. Three different numbers of thermal cycles were used, namely, 10, 100, and 500 cycles. Note, one thermal cycle equals room temperature to 270°F and back to room temperature. The test strengths were then compared to control strengths from unexposed panels (no thermal cycling), and are plotted in figures 182 and 183.

The following data summarizes the effect of thermal cycling on longitudinal and transverse flexure strengths as well as interlaminar shear strength of unidirectional Type AS/3002 graphite/epoxy laminates. Note the control strength in any case is the strength of an unexposed (to environment) panel.

Environment	Effect
Thermal cycling 10, 100, 500 cycles 1 cycle = RT to 270°F to RT	The room temperature and 270°F longitudinal flexure strengths were unaffected by thermal cycling. Similarly, the transverse flexure strengths at RT and 270°F were unaffected at 10 and 100 cycles. At 500 cycles, there was a 22% decrease in RT transverse flexure strength, and a 7% decrease in 270°F transverse flexure strength. The RT and 270°F interlaminar shear strengths were within 15% of the control values for 10 to 500 cycles. (See figures 182 and 183. Refer to table LXVIII.)

TABLE LXVIII. ENVIRONMENTAL EFFECTS DATA - THERMAL CYCLING - GRAPHITE/EPOXY - TYPE AS/3002 BATCH - $[0]_{13T}$

	Prior Exposure		Thermal Cycling RT to 270°F to RT					
			10 Cycles		100 Cycles		500 Cycles	
Test	Test Temp (°F)	Control Stress* (Ksi)	Stress* (Ksi)	% of Control	Stress* (Ksi)	% of Control	Stress* (Ksi)	% of Control
Longitudinal flexure	RT 270	217.0 (3) 225.0 (3)	233.0 (1) 237.0 (2)	107 105	237.0 (1) 236.0 (2)	109 105	232.0 (1) 219.0 (2)	107 97
Transverse flexure	RT 270	14.2 (3) 8.65 (3)	14.2 (1) 8.86 (2)	100 102	14.5 (1) 9.75 (2)	102 113	10.9 (1) 8.0 (2)	77 93
Interlaminar shear	RT 270	18.0 (3) 10.8 (3)	17.1 (1) 9.30 (2)	95 86	16.6 (1) 11.28 (2)	92 104	16.4 (1) 12.4 (2)	91 115

*Average of number of specimens shown in parentheses

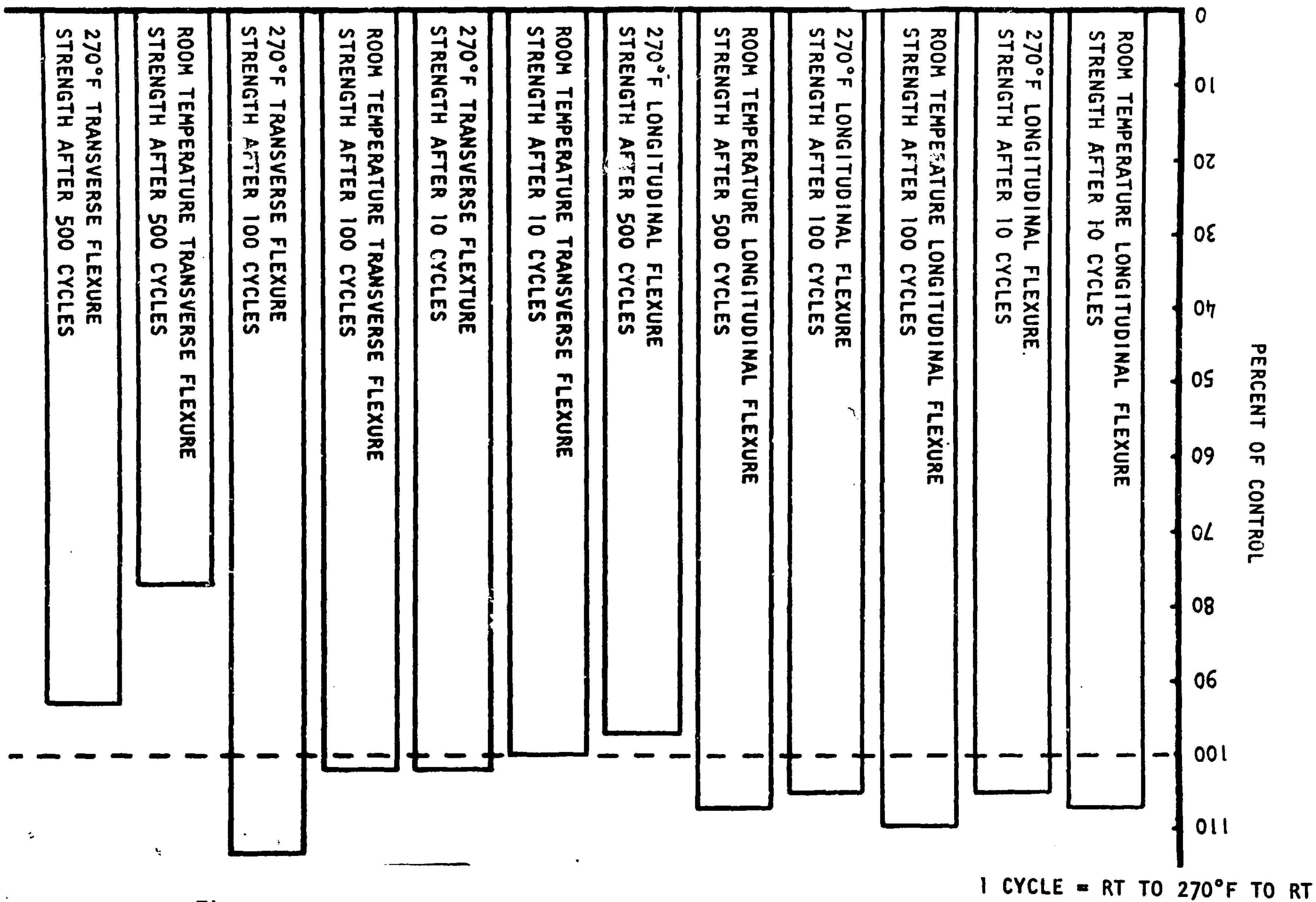


Figure 182. Longitudinal and Transverse Flexure Strengths for Unidirectional Laminates Previously Thermal Cycled - Type AS/3002 Batch Graphite/Epoxy

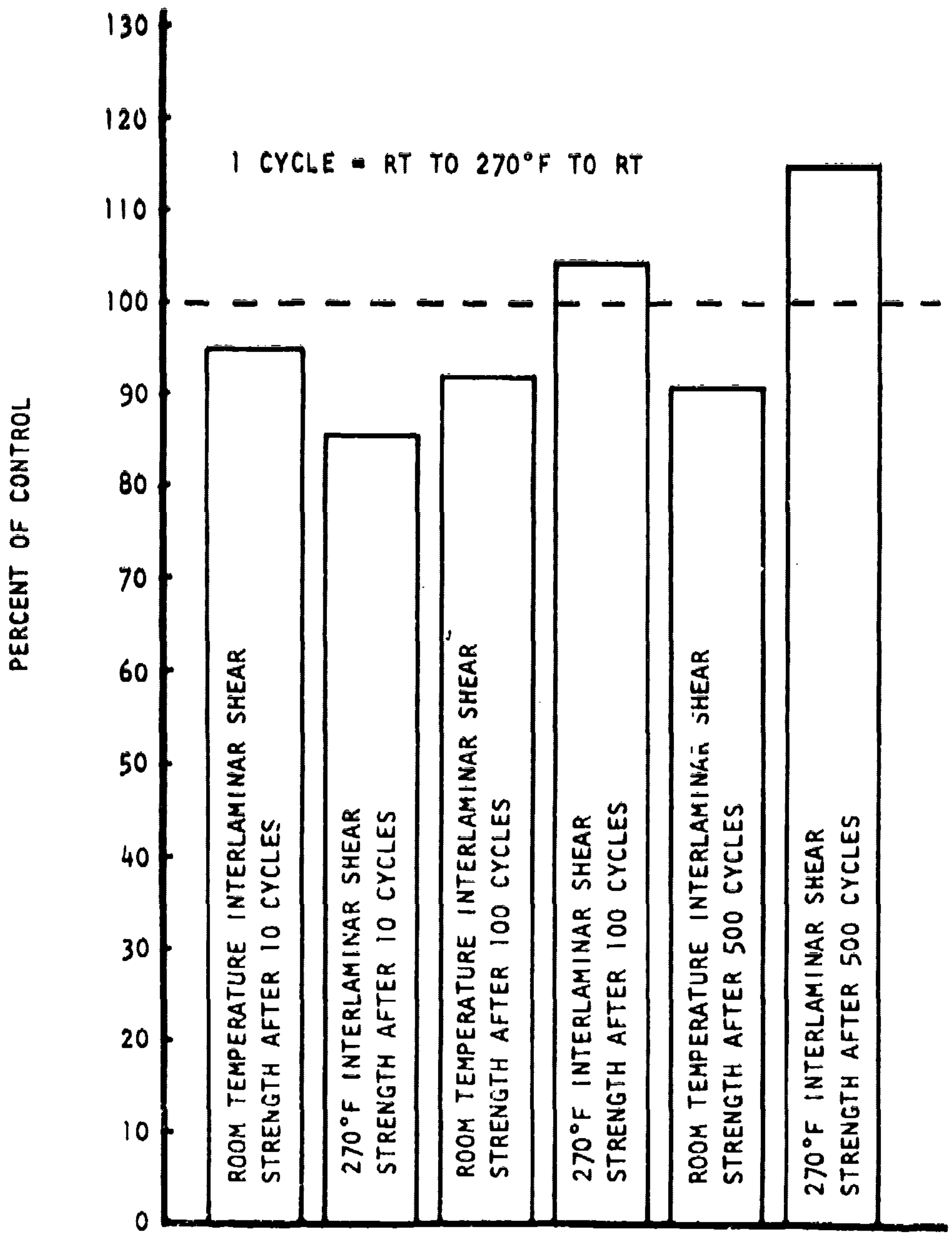


Figure 183. Interlaminar Shear Strengths for Unidirectional Laminates Previously Thermal Cycled - Type AS/3002 Batch Graphite/Epoxy

Effects on Bonded Joint Tension Strengths

Table LXIX contains room-temperature static tension data for adhesive (Metlbond 329-7) bonded single-lap (nominal 0.5-inch length) joints which were previously thermal cycled. The joint adherends were $[0/\pm45]_S$ graphite/epoxy Type AS/3002 - batch. Three different numbers of thermal cycles were used (10, 100, and 500), with one thermal cycle consisting of raising the temperature of the specimen from room temperature to 270°F and back to room temperature. The "residual" adhesive shear strength after thermal cycling was then compared to the strength of an unexposed single-lap joint. About a 15 to 30 percent reduction in joint strength was observed due to the thermal cycling. Figure 184 shows typical failed specimens. Note that, for all specimens, the failure mode was interlaminar shear in the laminate ply adjacent to the joint.

Figure 185 presents a graphical summary of the environmental effects of thermal cycling on the static room-temperature strength of single-lap bonded graphite/epoxy to graphite/epoxy joints. The chart shows that previous thermal cycling of RT to 270°F to RT for 10, 100, and 500 cycles reduces static strength to an average of 81 percent of control (ranged from 70 to 91 percent of control). Based on these limited number of tests, one concludes that static bonded lap joint strengths using Metlbond 329-7 adhesive are reduced by thermal cycling. This effect will be more significant for room temperature, rather than elevated temperature data, due to the greater inherent internal residual stresses in the bonded joint at room temperature.

TABLE LXIX. GRAPHITE/EPOXY BONDED LAP JOINT
STATIC ROOM TEMPERATURE TENSION DATA AFTER THERMAL CYCLING
ADHESIVE: METLBOND 329-7, ADHERENDS: $[0/\pm45]_S$ GRAPHITE/EPOXY, $[0/\pm45]_S$ GRAPHITE/EPOXY***

Specimen No.	Number of Thermal Cycles*	Adherend Thick. (in.)	Lap Length L_a (in.)	Load (lb)	Adhesive Shear Stress (psi)	Laminate Stress (Ksi)	Adhesive Shear Stress / Control**
BGGTC-6LA-1	10	0.039	0.54	835	1,546	21.41	0.70
BGGTC-6LA-2	10	0.037	0.56	900	1,607	24.32	0.73
BGGTC-6LA-3	10	0.038	0.55	895	1,627	23.55	0.74
Avg					(1,593)	(23.09)	(0.72)
BGGT-6LA-4	100	0.038	0.52	1,020	1,962	26.84	0.89
BGGTC-6LA-5	100	0.038	0.52	900	1,731	23.68	0.79
BGGTC-6LA-6	100	0.038	0.51	1,000	1,961	26.32	0.89
Avg					(1,885)	(25.61)	(0.86)
BGGTC-6LA-7	500	0.039	0.51	1,025	2,010	26.28	0.91
BGGTC-6LA-8	500	0.038	0.50	960	1,920	26.97	0.87
BGGTC-6LA-9	500	0.038	0.52	889	1,692	23.16	0.77
Avg					(1,873)	(25.47)	(0.85)

*One thermal cycle = RT to 270°F to RT
**Control stress from unexposed lap joint test (table XXXIII)
***Type AS/3002 Batch Graphite/Epoxy

NOTE Width, w = 1.0 inch
Failure mode = interlaminar shear in laminate

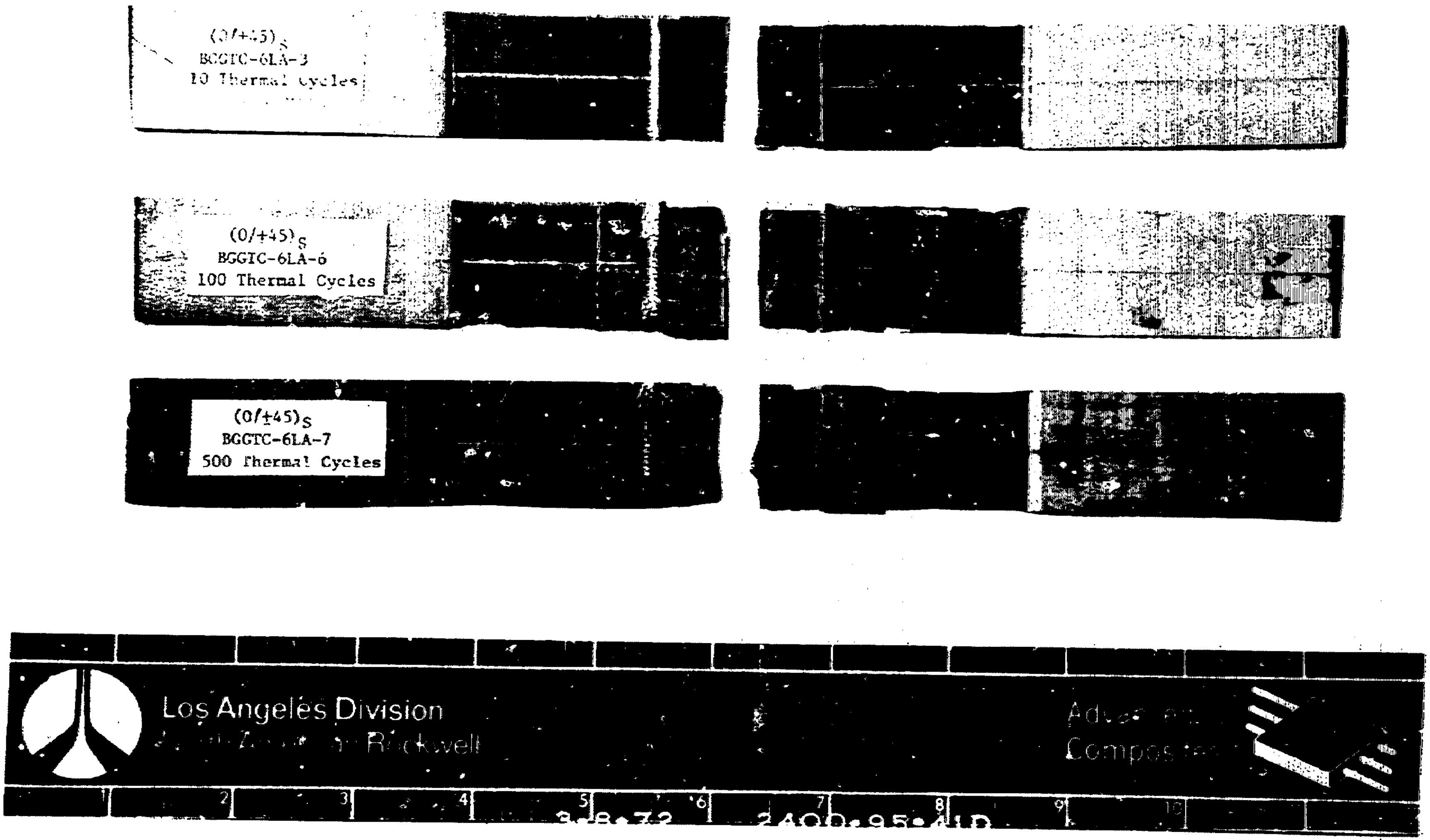


Figure 184. Failed Static Tension Bonded Single Lap Joint Specimens - Graphite/Epoxy Adherends (Type AS/3002 Batch), Metlbond 329-7 Adhesive - Thermal Cycled Before Testing

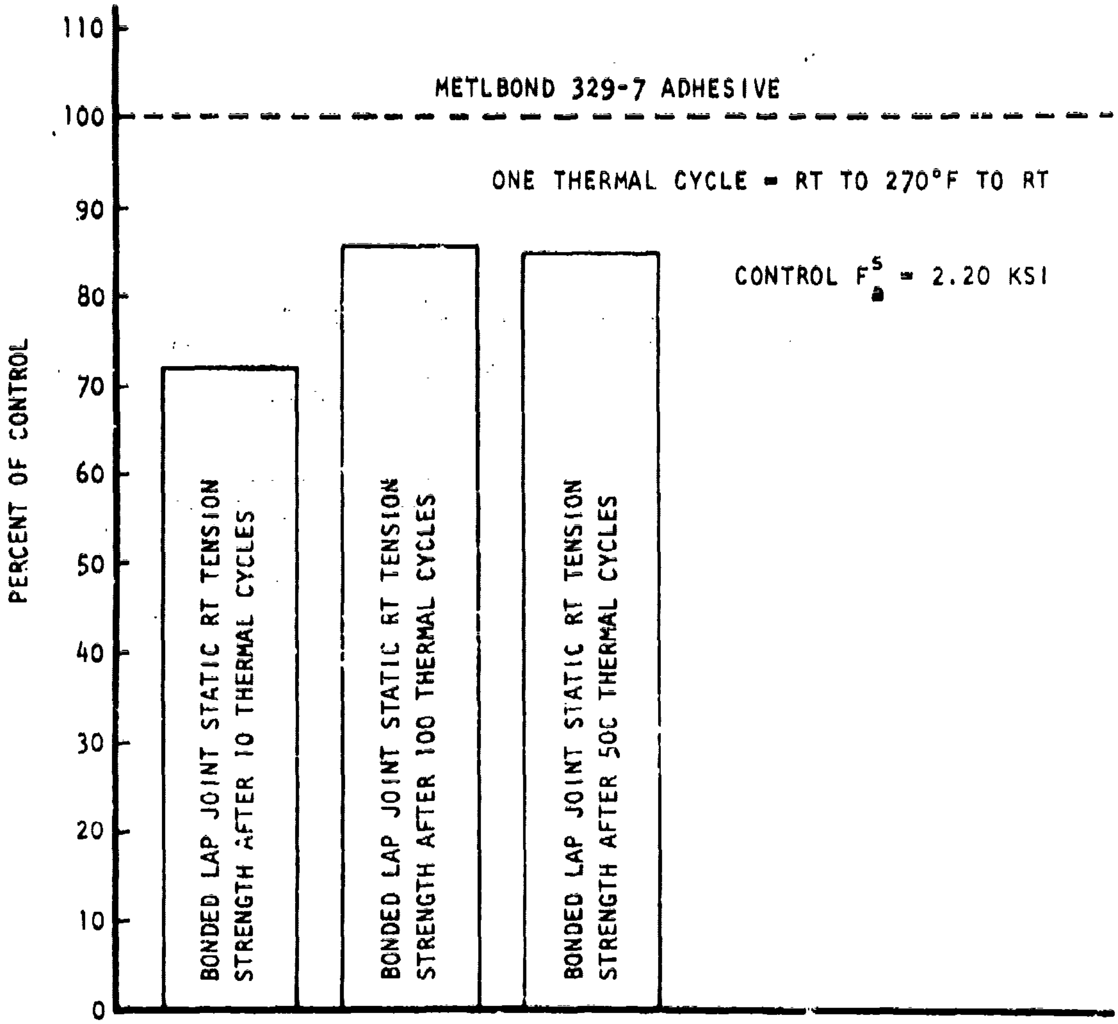


Figure 185. Room Temperature Graphite/Epoxy to Graphite/Epoxy Single Lap Bonded Joint Adhesive Shear Strengths for $[0/\pm45]_S$ Laminates Previously Thermal Cycled - Type AS/3002 Batch

Effects on Mechanical Joint Tension Strengths

Table LXX presents room-temperature and 275°F tension data for previously thermal cycled single-lap mechanical joint specimens with e/D ratios of 2.63 and flush head (No. 10) screw fastener. Environmental exposures consisted of 10, 100, and 500 thermal cycles (one cycle = RT to 270°F to RT). The bearing strengths of the thermally cycled joints were then compared to that of an unexposed single-lap graphite/epoxy-to-steel mechanical specimen. Figure 186 shows typical failed specimens. Note that all failures were of the bearing mode.

Figure 187 provides a graphical presentation of static mechanically fastened joint strengths of specimens which had been previously thermally cycled. The chart shows that mechanically fastened joints are not affected by thermal cycling exposures of RT to 275°F to RT.

TABLE LXX. SINGLE LAP MECHANICAL
JOINT ENVIRONMENTAL DATA - THERMAL CYCLING*
TYPE AS/3002 BATCH GRAPHITE/EPOXY - $[0/\pm45]_{4S}$ LAMINATE (24 PLIES)

Specimen No.	Actual Width w (in.)	Actual Thick. t (in.)	Edge Distance e (in.)	Prior Thermal Cycling	Test Temp (°F)	Failure Load (lb)	Failure Stresses Bearing (Ksi)	Shear-out (Ksi)	Net Tension (Ksi)	Bearing Stress/ Control
FHTTC-24LA-1	1.001	0.1469	0.499	10	RT	2,460	88.0	20.7	20.7	1.11
FHTTC-24LA-2	1.002	0.1433	0.500	10	275	1,975	72.6	17.0	17.0	1.10
FHTTC-24LA-3	1.002	0.1455	0.500	10	275	1,850	66.9	15.7	15.7	1.01
Avg					275	(1,913)	(69.8)	(16.4)	(16.4)	(1.06)
FHTTC-24LA-4	1.003	0.1513	0.495	100	RT	2,200	76.6	18.0	18.0	0.96
FHTTC-24LA-5	1.000	0.1460	0.494	100	275	2,050	73.9	17.4	17.4	1.12
FHTTC-24LA-6	1.002	0.1498	0.500	100	275	1,970	69.2	16.2	16.2	1.05
Avg					275	(2,010)	(71.6)	(16.8)	(16.8)	(1.09)
FHTTC-24LA-7	1.002	0.1474	0.501	500	RT	2,220	79.1	18.6	18.6	1.00
FHTTC-24LA-8	1.002	0.1458	0.499	500	275	2,050	74.0	17.4	17.4	1.12
FHTTC-24LA-9	1.002	0.1510	0.503	500	275	1,830	63.8	15.0	15.0	0.97
Avg					275	(3,940)	(68.9)	(16.2)	(16.2)	(1.04)

NOTE Average t = 0.1474
One thermal cycle = RT to 275°F to RT (prior exposure)
All failures were primarily bearing mode
Control stress from unexposed (no thermal cycling) test specimens of same type of mechanical single lap joint. 275°F control bearing strength values are interpolated values.

*Fastener: flush head (No. 10) screw, 160 Ksi heat treat
Nominal: e/D = 2.63, S/D = 2.63, t = 0.144 in., and D = 0.19 in.

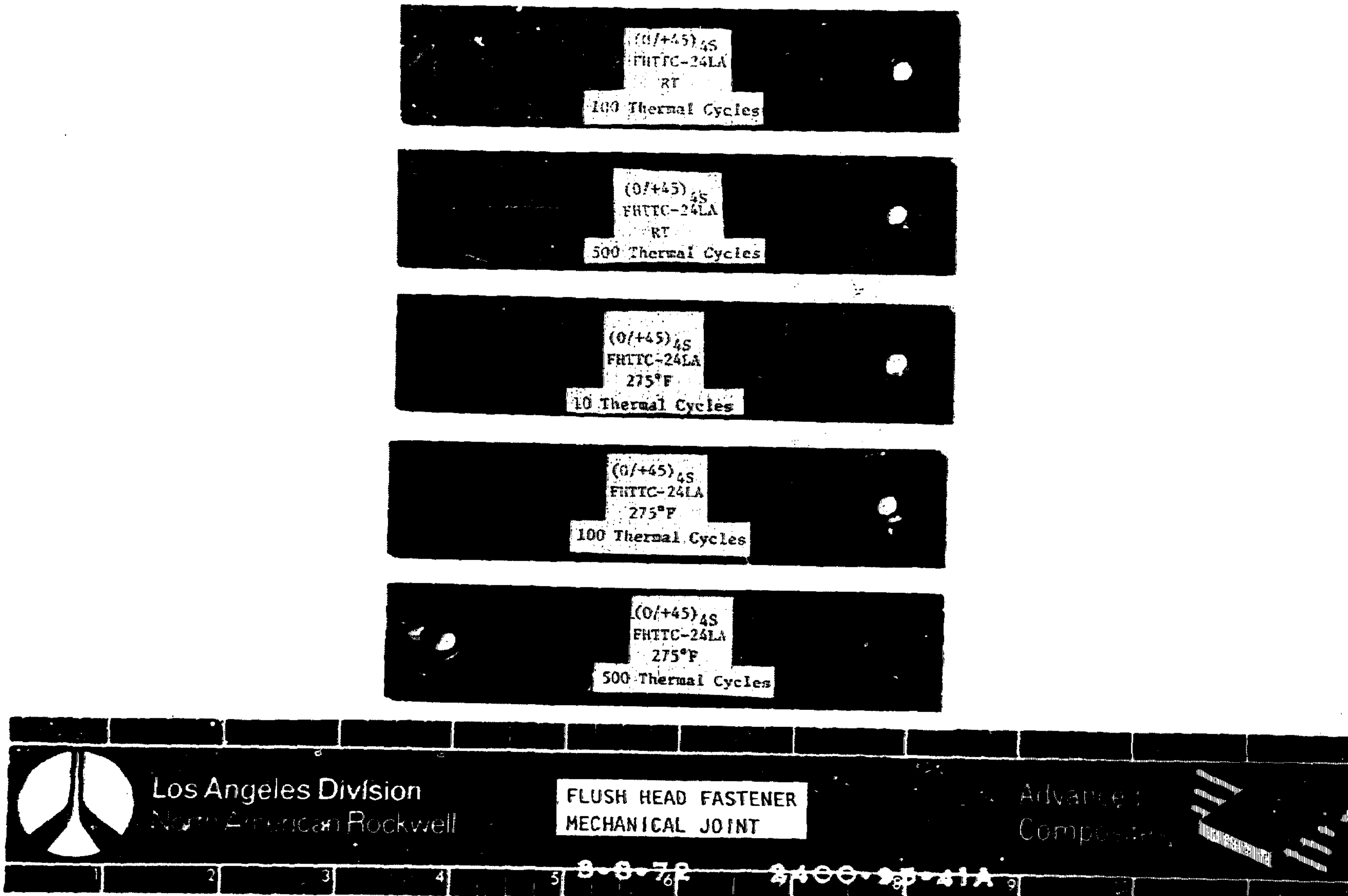


Figure 186. Failed Single Lap Mechanical Joint Specimens - $[0/\pm45]_{4S}$ Graphite/Epoxy (Type AS/3002 Batch), c/D (Nominal) = 2.63, Specimens Previously Thermal Cycled

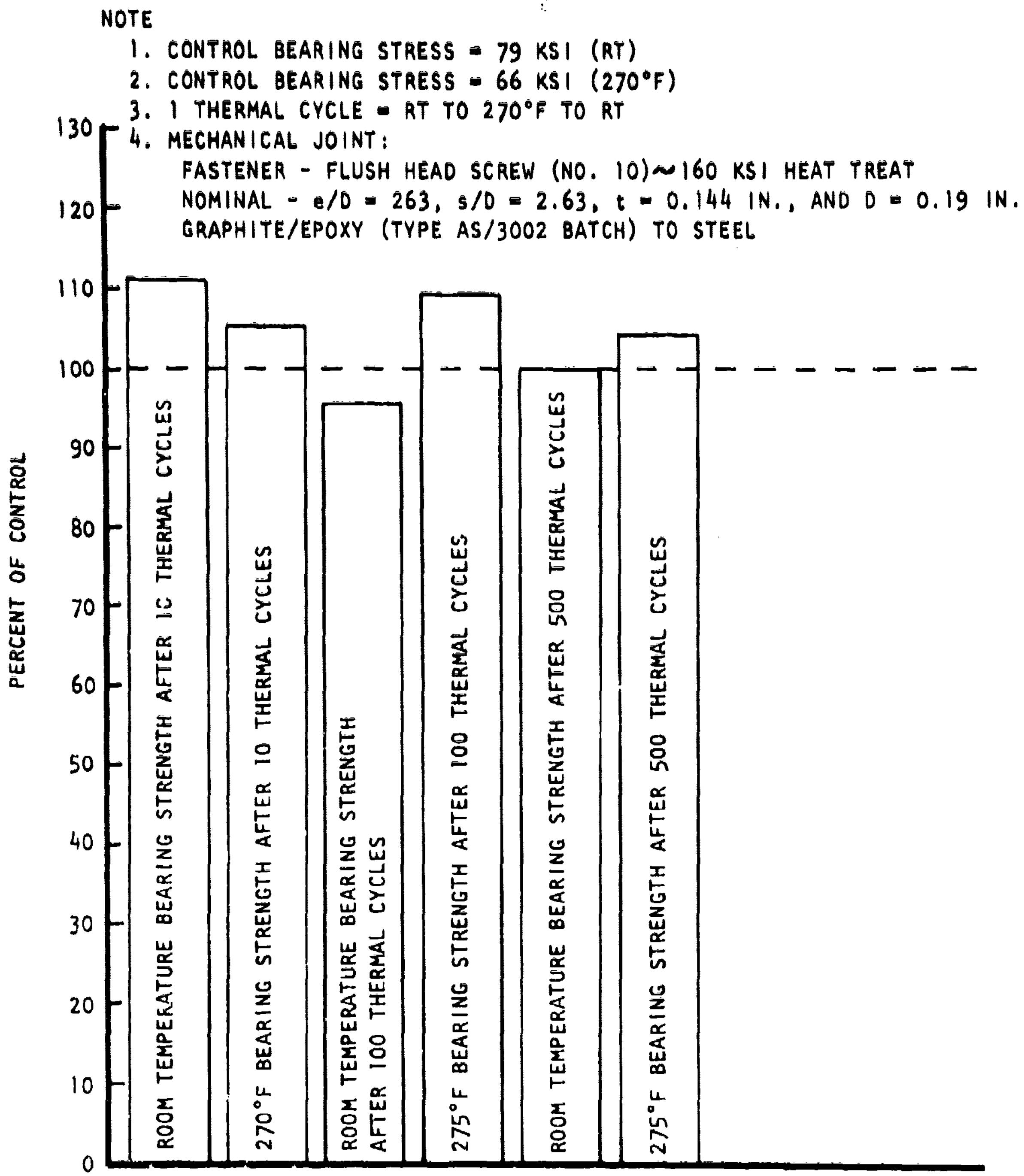


Figure 187. Environmental Effects on Bearing Strength of Single Lap Mechanical Joints Previously Thermal Cycled, - Graphite/Epoxy $[0/\pm 45]_{4S}$

Effects of Nuclear Radiation on Q.C. Values

Table LXXI presents nuclear radiation exposure data for unidirectional graphite/epoxy panels tested within the Northrop Reactor dry exposure room, with the 1/4-inch boral shield in position around the exposure room window. Longitudinal flexure, transverse flexure, and horizontal shear tests of the exposed panels were conducted and are summarized in table LXXII, compared with unexposed control values. No degradations in strength properties were evident for either the flexure or horizontal shear data, as can be observed from table LXXII.

TABLE LXXI. NUCLEAR RADIATION DATA FOR GRAPHITE/EPOXY PANELS - TYPE AS/3002 BATCH

Panel Series No.*	Neutron Fluence			Gamma Dose	
	$N/cm^2 > 3$ Mev	$N/cm^2 > 10$ Kev	1 Mev (Si) Damage Equivalent	Roentgens	Rads-Silicon
R-1**	3.91×10^{10}	4.03×10^{11}	3.60×10^{11}	8.4×10^{2}	7.1×10^{2}
R-2**	9.47×10^{10}	9.75×10^{11}	8.71×10^{11}	9.8×10^{2}	8.3×10^{2}
R-3**	9.15×10^{11}	9.42×10^{11}	8.42×10^{12}	2.6×10^{3}	2.2×10^{3}

*Test coupons were cut from panel after exposure for example: Longitudinal flexure coupon R-1-1 was cut from panel R-1; transverse flexure coupon R-3-1 was cut from panel R-3; etc.

**$[0]_{13T}$ graphite/epoxy laminates

TABLE LXXII. QUALITY CONTROL TEST DATA FOR NUCLEAR RADIATED UNIDIRECTIONAL GRAPHITE/EPOXY LAMINATE - TYPE AS/3002 BATCH

Test*	Control	Panel R-1		Panel R-2		Panel R-3	
		Test Value	% of Average Control Stress	Test Value	% of Average Control Stress	Test Value	% of Average Control Stress
Longitudinal flexure, F_L^{flex} (Ksi)	251.0	251.2	105.0	247.7	103.8	243.4	102.0
	230.9	238.0	100.0	233.6	97.9	240.6	100.8
	233.7	241.3	101.0	231.8	97.2	245.9	103.1
Avg	(238.6)	(243.5)	(102.0)	(237.7)	(99.6)	(243.3)	(102.0)
Transverse flexure, F_T^{flex} (Ksi)	---	7.21	---	7.19	---	7.38	---
	---	7.37	---	7.43	---	7.33	---
	---	6.68	---	7.71	---	6.21	---
Avg	---	(7.09)	---	(7.44)	---	(6.97)	---
Horizontal shear, F^{isu} (Ksi)	17.36	17.49	100.8	17.48	100.8	16.96	97.7
	17.26	17.78	102.4	17.97	103.5	17.16	98.9
	17.46	17.71	102.0	17.61	101.4	16.57	95.5
Avg	(17.36)	(17.65)	(101.7)	(17.69)	(101.9)	(16.90)	(97.4)

NOTE Refer to table LXXI for neutron fluence and gamma dose data.

*All tests conducted at room temperature

Effects of Thermal Pulses on Tension and Compression Properties

Tables LXXIII and LXXIV present room-temperature and 270°F tension and compression data for coated and uncoated crossplied test specimens which were previously exposed to a series of simulated nuclear blast thermal pulses with a 15 Ksi preload. The coated specimens were first coated with HYSOL conductive coating K9-4239, then painted with a flat black outer paint.* The test setup and fabricated specimens (before and after exposure) are shown in figures 188 through 191, while typical failed specimens are included in figures 192 through 195. Note that the irregular spot, visible on the exposed (thermal pulsed) specimens, defines the middle of the exposure test section and thermocouple locations. Laminate damage was visually apparent only on the $[0/\pm45/90]_S$ short column compression test specimen shown in figures 190 and 191. The resulting "residual" strengths and moduli are compared to values from unexposed, uncoated static test specimens. Note the failure modes included in tables LXXIII and LXXIV.

Figures 196 and 197 present graphical displays of the effect of simulated nuclear blast - thermal pulses on the static tensile and compressive properties of Type AS/3002 graphite/epoxy laminates of $[0/\pm45]_S$ and $[0/\pm45/90]_S$, respectively. The charts show that the strength degradation, due to prior exposure to a series of simulated nuclear blast thermal pulses with 15 Ksi preload, was greater for the coated (lightning strike protection) specimens than uncoated specimens. The average degraded strength was 78 percent of uncoated control data (range of 55 to 91 percent). Based on this preliminary data, thermal pulse effects should be accounted for (approximately 20-percent strength reduction) where laminates are expected to maintain ultimate strength levels, even after thermal pulse exposure levels. Additional tests of the specific design configuration are recommended, since the failures occurred in the tab regions. The initial modulus values in both tension and compression are generally not significantly affected by the thermal pulse prior exposure. Exposed specimens had values which averaged 93 percent of control, with a range of 79 to 102 percent of control. It can be concluded that the overall stiffness of the laminates will not be affected by thermal pulse effects.

*The paint was utilized to assure that each specimen was a "black body" that would absorb the proper thermal load.

TABLE LXXIII. CROSSPLIED GRAPHITE/EPOXY TENSION DATA FOR IITRI COUPONS SPECIMENS PREVIOUSLY EXPOSED TO THERMAL PULSE - TYPE AS/3002-BATCH GRAPHITE/EPOXY

Orientation	Specimen No.	Temp (°F)	Specimen ***	Static Control		Residual**		Percent of Control		Failure Mode
				Strength (Ksi)	Modulus (Msi)	Strength (Ksi)	Modulus (Msi)	Strength	Modulus	
$[0/\pm45]_S$	TTP-6L-1C	RT	Coated	----	----	38.6	7.72	56.8*	96.4*	1
	TTP-6L-2C	270	Coated	----	----	46.0	7.23	72.0*	97.7*	1
	TTP-6L-3U	270	Uncoated	64.0	7.40	61.6	8.14	90.7	101.6	2
		RT	Uncoated	68.0	8.01					
$[0/\pm45/90]_S$	TTP-8L-1C	RT	Coated	----	----	51.2	7.20	80.1*	97.3*	1
	TTP-8L-2C	270	Coated	----	----	44.0	5.65	73.5*	79.0*	1
	TTP-8L-3U	270	Uncoated	60.0	7.15	53.3	6.83	83.3	92.3	1
		RT	Uncoated	64.0	7.39					1

*Percent of uncoated static control
**Prior exposure to a series of simulated nuclear blast thermal pulses with 15 Ksi preload
***Coated specimens have a coating of HYSOL conductive coating K9-4239, Hardener H2-3487 plus flat black paint outer coat

NOTE Failure Mode Code = 1 = failure under tabs; 2 = failure in test section
Static control data for specimens TTP-6L-3U and TTP-8L-3U interpolated from RT and 350°F data

TABLE LXXIV. CROSSPLIED GRAPHITE/EPOXY COMPRESSION DATA FOR EDGEWISE SANDWICH SPECIMENS PREVIOUSLY EXPOSED TO THERMAL PULSE - TYPE AS/3002-BATCH GRAPHITE/EPOXY

Orientation	Specimen No.	Temp (°F)	Specimen ****	Static Control		Residual***		Percent of Control		Failure Mode
				Strength (Ksi)	Modulus (Msi)	Strength (Ksi)	Modulus** (Msi)	Strength	Modulus	
$[0/\pm45]_S$	ECTP-6L1C	RT	Coated			66.5	10.56	88.0*	92.9*	1
	ECTP-6L2C	270	Coated			59.6	9.82	82.0*	102.8*	1
	ECTP-6L3U	RT	Uncoated	76.0	11.37					1
	ECTP-6L4U	270	Uncoated	72.0	9.55					1
$[0/\pm45/90]_S$	ECTP-8L1C	RT	Coated			42.3	8.83	55.0*	90.0*	1
	ECTP-8L2C	270	Coated			47.9	7.18	91.0*	83.6*	2
	ECTP-8L3U	RT	Uncoated	77.0	9.81					1
	ECTP-8L4U	270	Uncoated	53.0	8.59					1

*Percent of uncoated static

**From head deflection extensometer data

***Prior exposure to a series of simulated nuclear blast thermal pulses with 15 Ksi preload

****Coated specimens have a coating of Hysol conductive coating K9-4239, hardener H2-3487 plus flat black paint outer coat

NOTE Failure mode code: 1 = failure in both face sheets at test section; 2 = failure under tabs

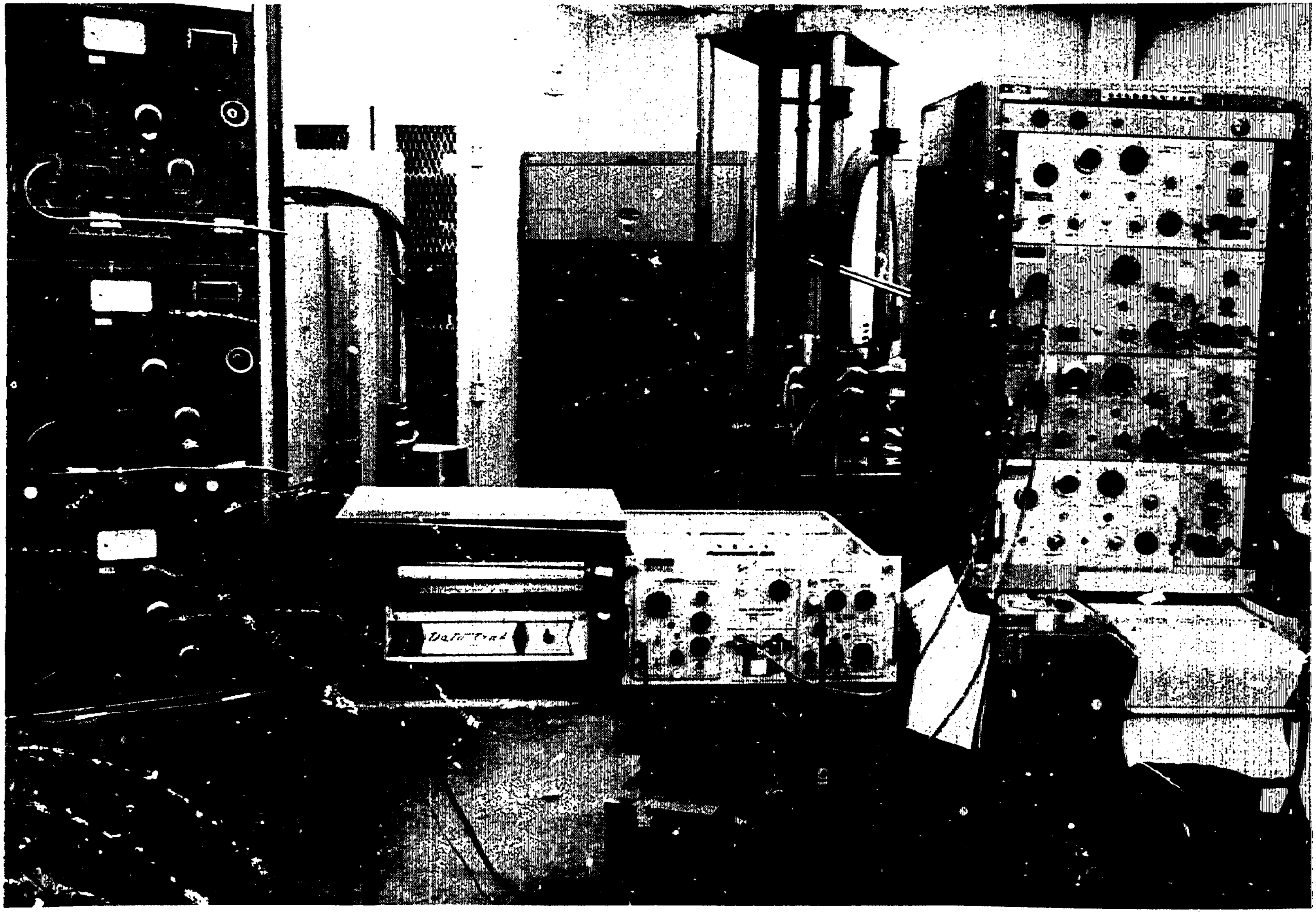


Figure 188. Test Setup for Thermal Pulse

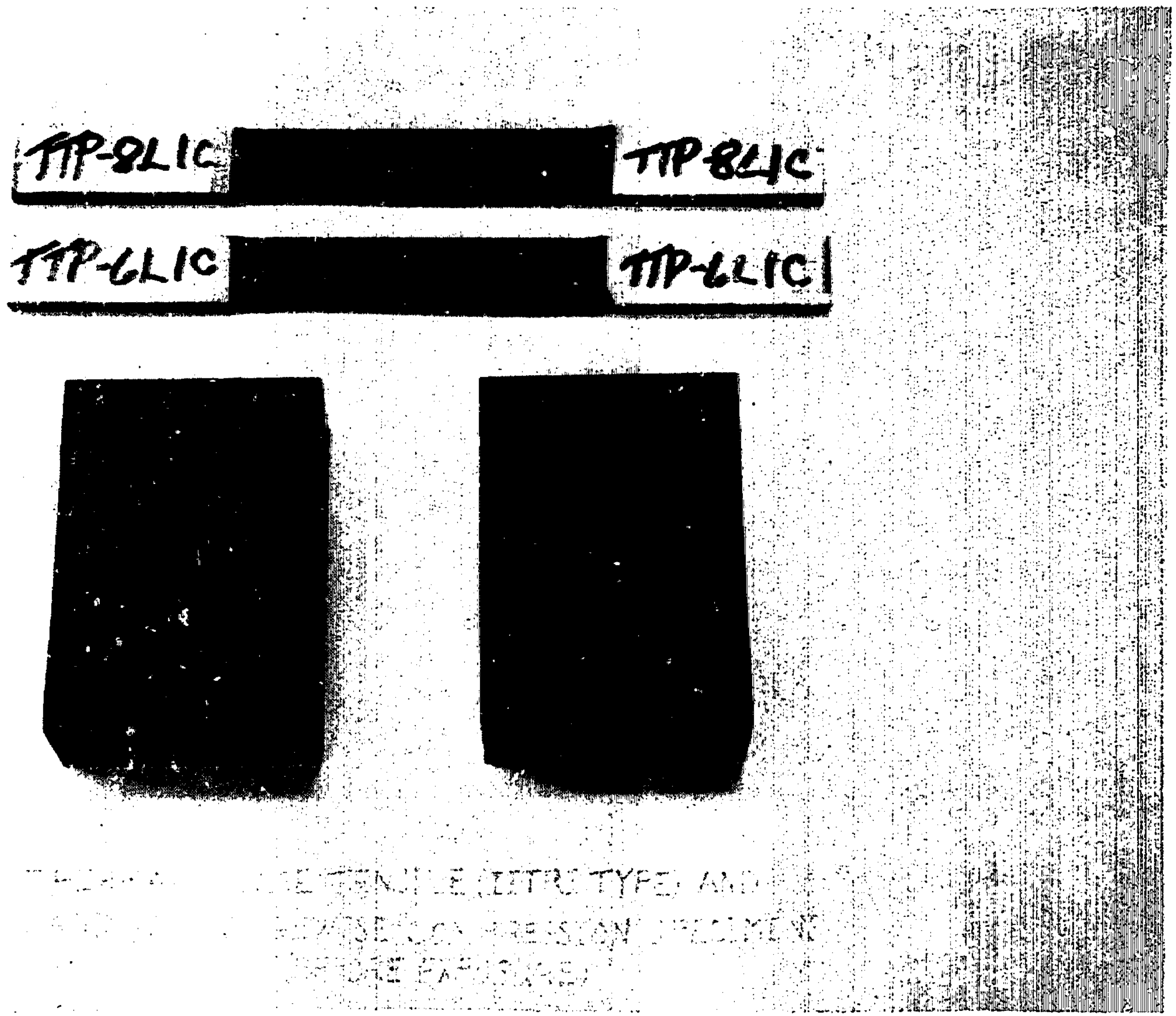


Figure 189. Thermal Pulse Tensile (IITRI Type) and Sandwich Edgewise Compression Specimens - Before Exposure

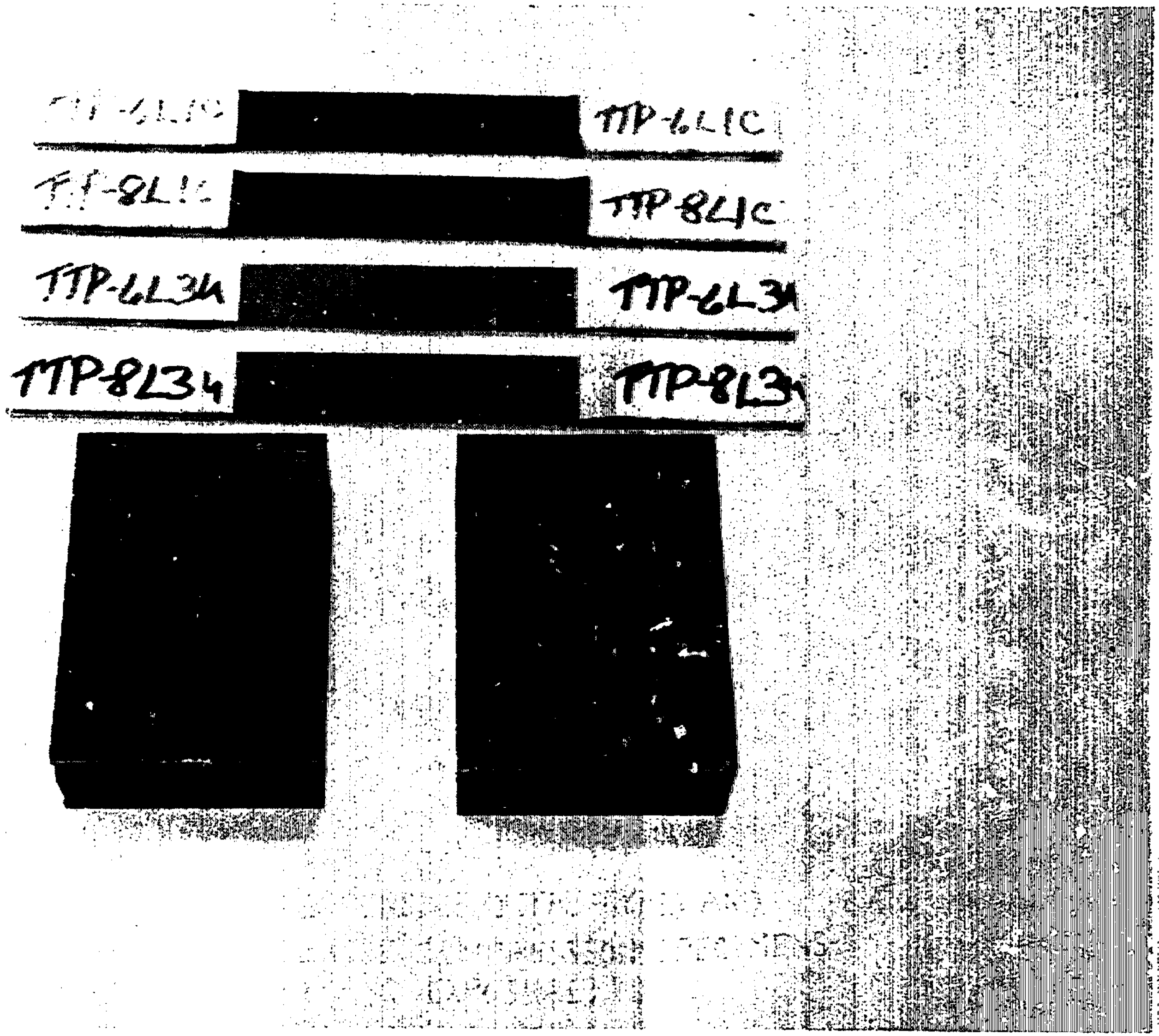


Figure 190. Thermal Pulse Tensile (IITRI Type) and Sandwich Edgewise Compression Specimens - After Exposure

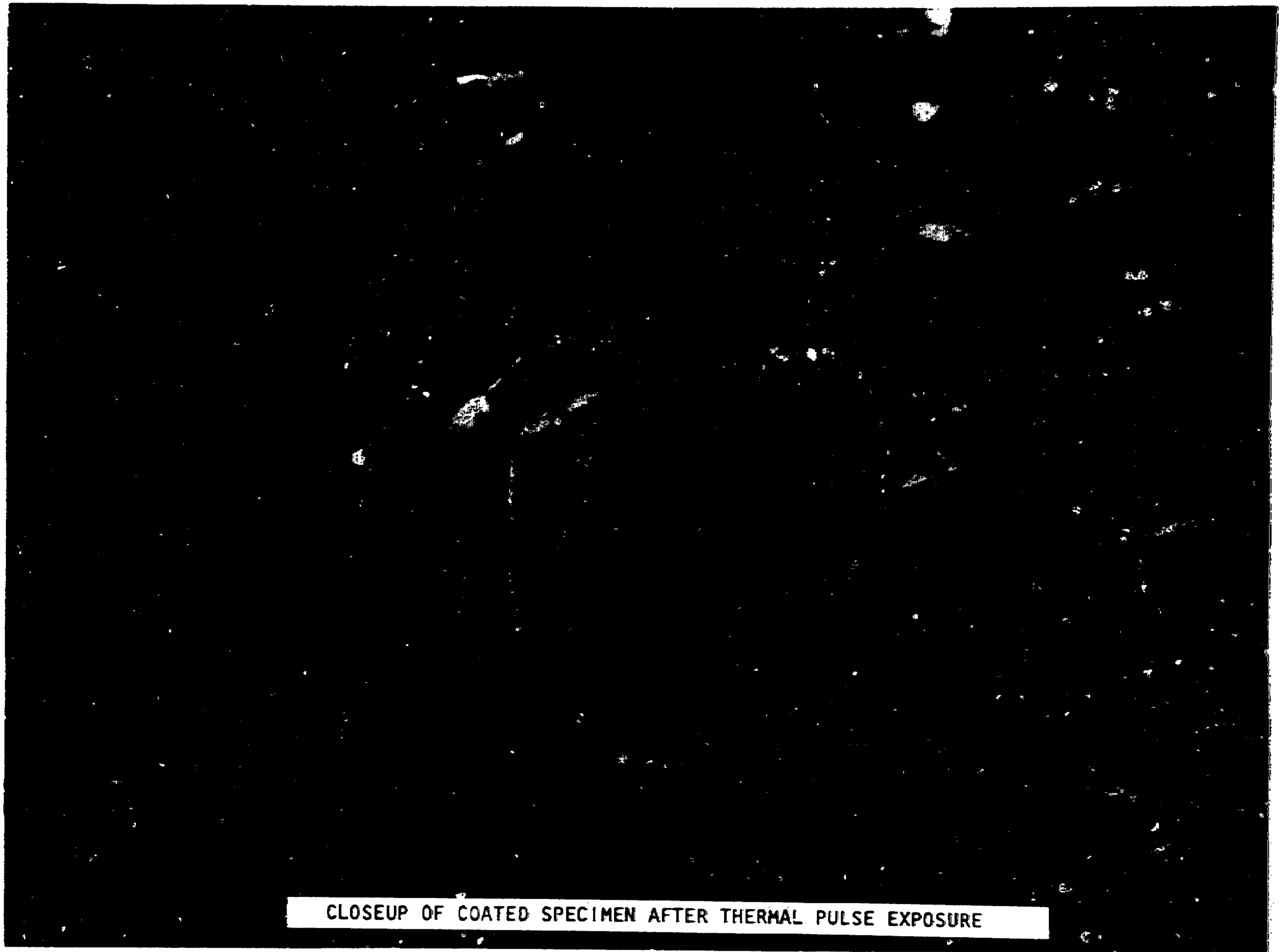


Figure 191. Thermal Pulsed Edgewise Compression Specimen - Coated Surface - After Exposure

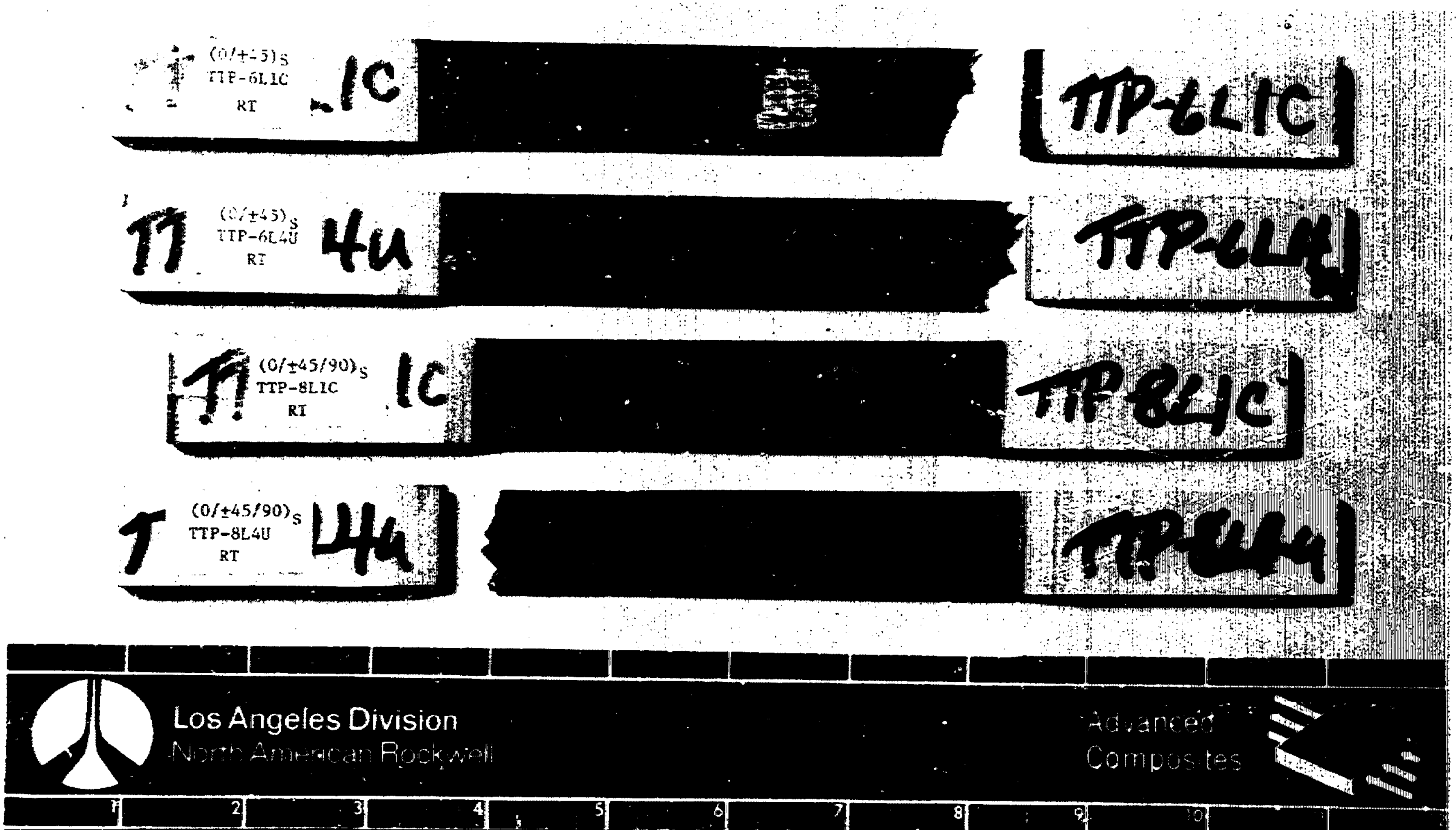


Figure 192. Failed Room Temperature Crossplied Tension Specimens Previously Thermal Pulsed, Graphite/Epoxy (Type AS/3002 Batch)

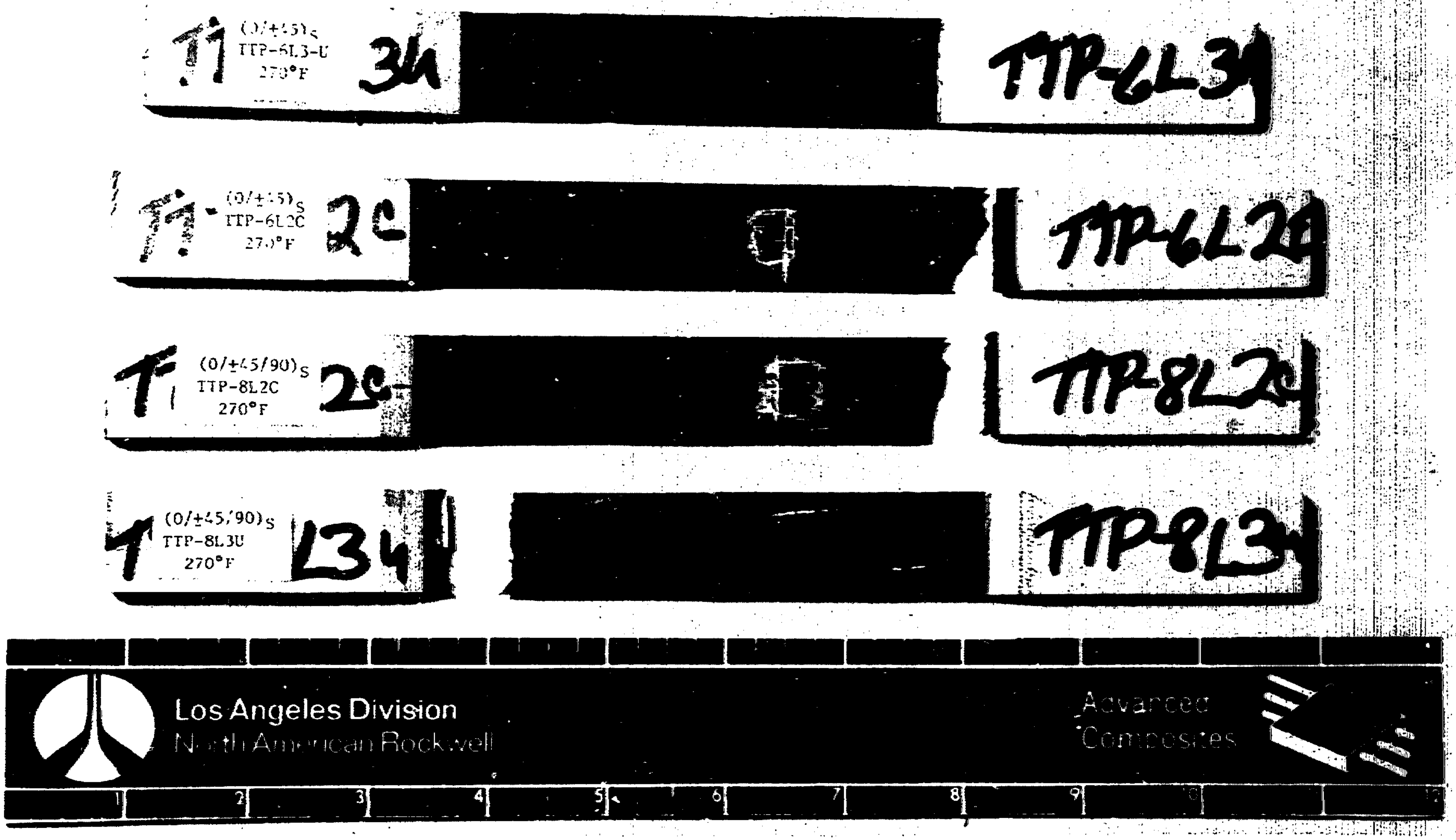


Figure 193. Failed 270°F Crossplied Tension Specimens Previously Thermal Pulsed, Graphite/Epoxy (Type AS/3002 Batch)

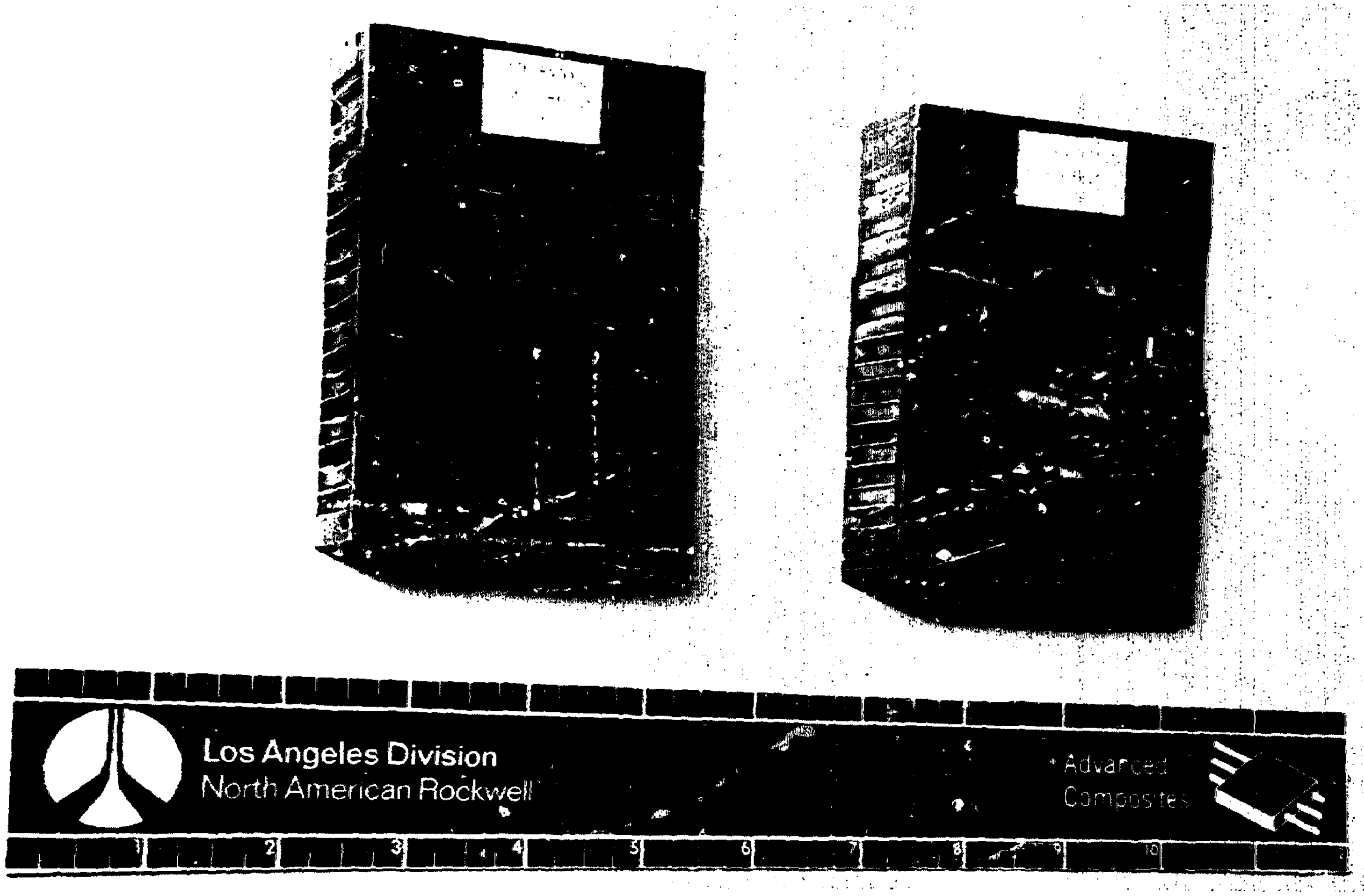


Figure 194. Failed Room Temperature Crossplied Compression Specimens Previously Thermal Pulsed, Graphite/Epoxy (Type AS/3002 Batch)

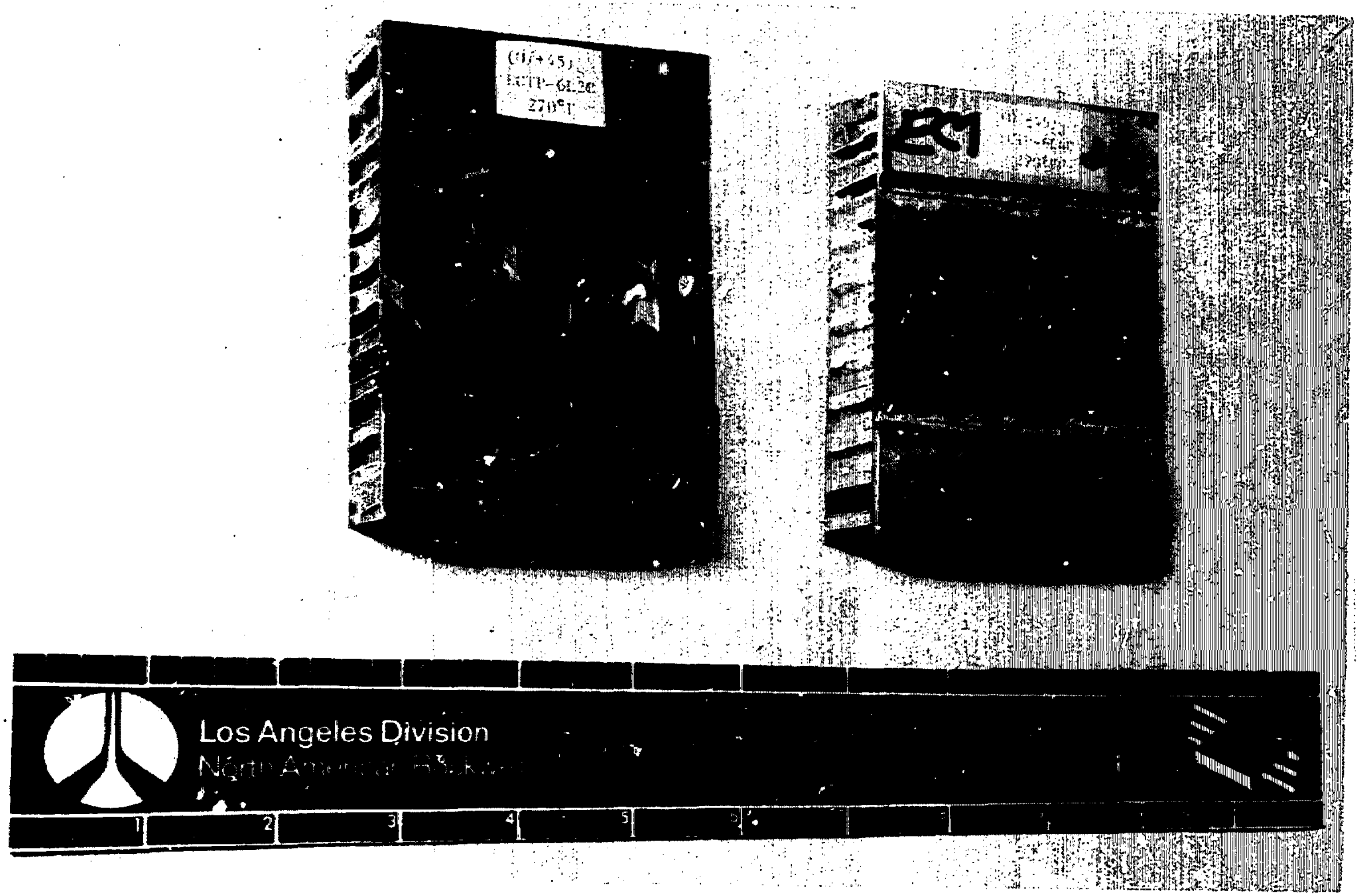
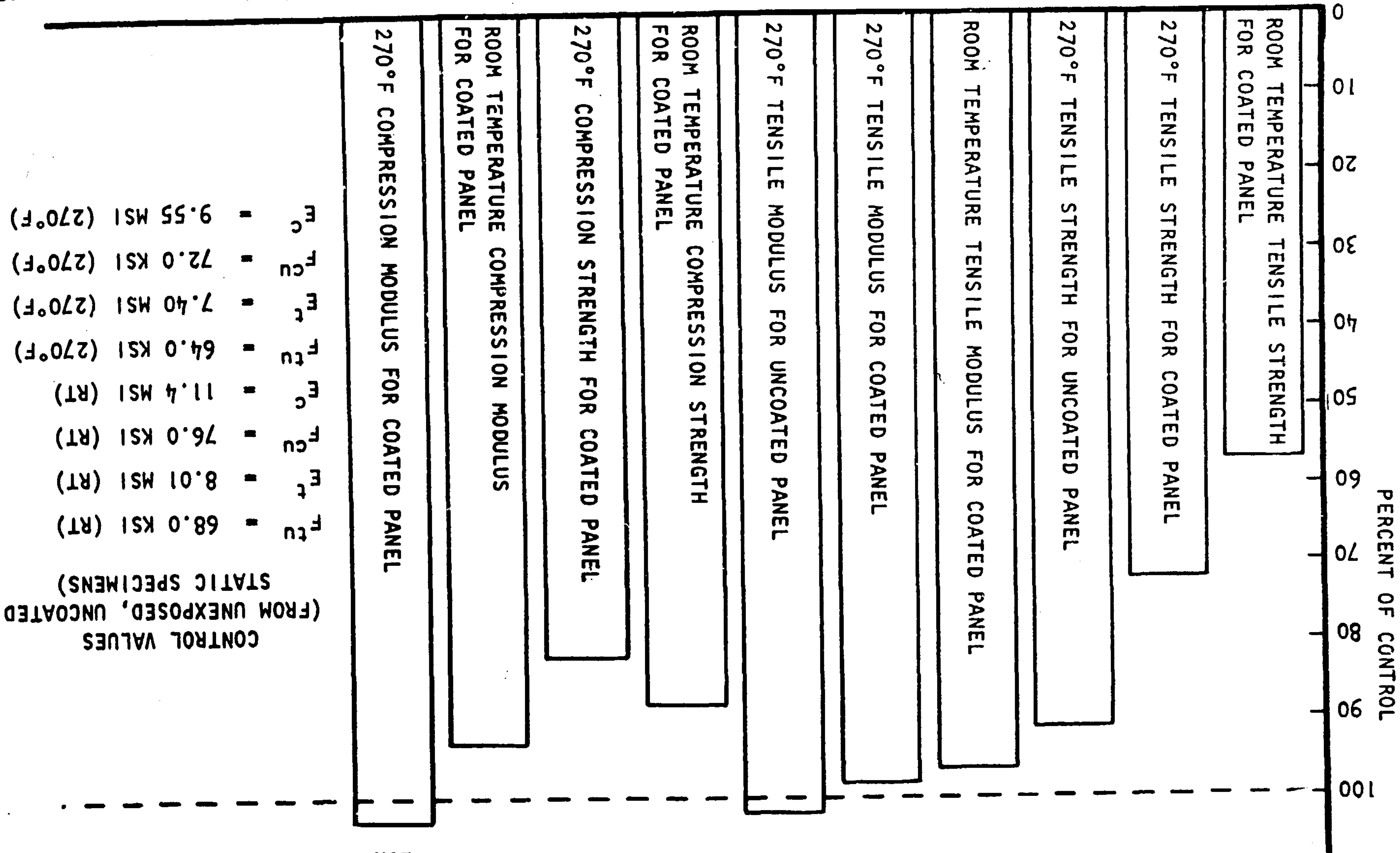


Figure 195. Failed 270°F Crossplied Compression Specimens Previously Thermal Pulsed, Graphite/Epoxy (Type AS/3002 Batch)

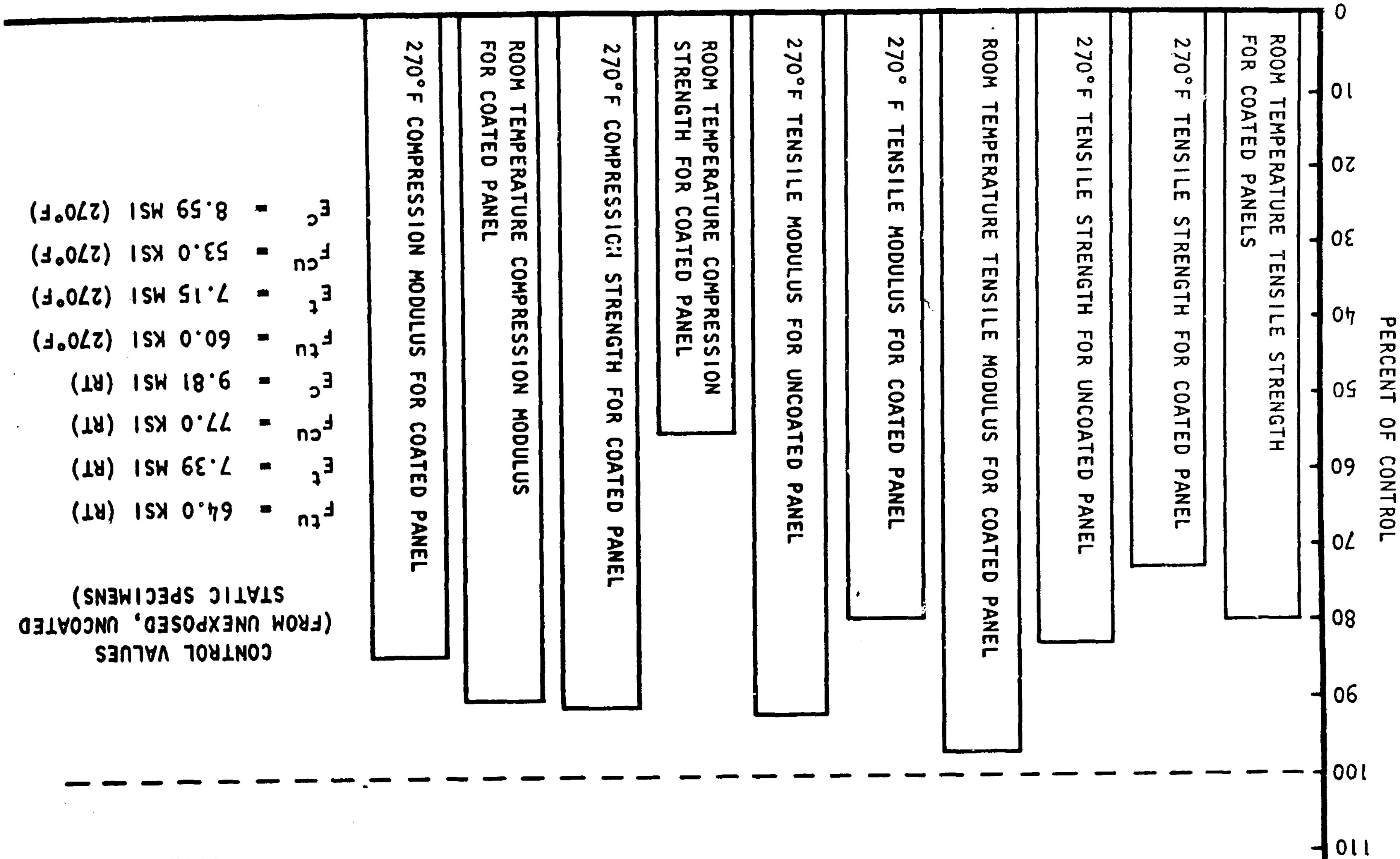
Figure 196. Environmental Effects Data for $[0/\pm45]_S$ Graphite/Epoxy Laminates Previously Exposed to Simulated Nuclear Blast Thermal Pulses



NOTE

1. PRIOR EXPOSURE TO A SERIES OF SIMULATED NUCLEAR BLAST THERMAL PULSES WITH A 15 KSI PRELOAD
2. COATED SPECIMENS HAVE A COATING OF HYSOL CONDUCTIVE COATING K9-4239

Figure 197. Environmental Effects Data for $[0/\pm45/90]_S$ Graphite/Epoxy Laminates Previously Exposed to Simulated Nuclear Blast Thermal Pulses



NOTE

1. PRIOR EXPOSURE TO A SERIES OF SIMULATED NUCLEAR BLAST THERMAL PULSES WITH A 15 KSI PRELOAD
2. COATED SPECIMENS HAVE A COATING OF HYSOL CONDUCTIVE COATING K9-4239

MISCELLANEOUS ENVIRONMENTS

Effects of Humidity, Salt Spray, and Weathering on Q.C. Properties

Table LXXV summarizes test data for unidirectional (Type AS/3002 - batch) graphite/epoxy specimens which were previously exposed to humidity, salt spray, or weathering environments. The various environments were as follows:

1.	98% relative humidity 120°F for 35 days	(humidity)
2.	5% salt solution 95°F for 35 days	(salt spray)
3.	Uncoated graphite/ epoxy panels left on rooftop for 35 days	(weathering)
4.	Graphite/epoxy panels coated with HYSOL epoxy conductive coating K9-4239 left on rooftop for 35 days	(weathering)

Longitudinal and transverse flexure, as well as interlaminar shear tests, were run after exposure. Room, 270°F, 350°F, and -65°F temperatures were used. The test results are also presented graphically in figures 198 through 200 where they are compared to the "control" values. The control values are the strength values from unexposed specimens.

An examination of the charts shown in figures 198 through 200 yields the conclusions (about the effects of the various environments) shown in the following list.

Environment	Effect
98% relative humidity 120°F for 35 days	The room-temperature longitudinal flexure strength was unaffected by the humidity exposure. The 270° and 350°F longitudinal flexure strength were 60 and 70% lower than controls. While room, 270°, and 350°F transverse flexure and interlaminar shear strength were reduced by 10 to 75%. (See figures 198 through 200. Refer to table LXXV.)
Salt spray 5% salt solution 95°F for 35 days	The room-temperature longitudinal flexure strength was unaffected, while the 270° and 350°F longitudinal flexure strengths were reduced by 13 and 53%, respectively. The room and 270°F transverse flexure strengths were decreased by 36%, and the 350°F transverse flexure strength was unaffected. The room, 270°, and 350°F interlaminar shear strengths were reduced by 14, 33, and 40%, respectively. (See figures 198 through 200. Refer to table LXXV.)
Weathering. Panel placed on roof top for 35 days	Room temperature and 270°F longitudinal flexure and interlaminar shear strengths were unaffected by weathering of both coated and uncoated panels. Coated panels had a HYSOL Epoxy Conductive Coating (K9-4239). See figures 198 through 200. Refer to table LXXV.)

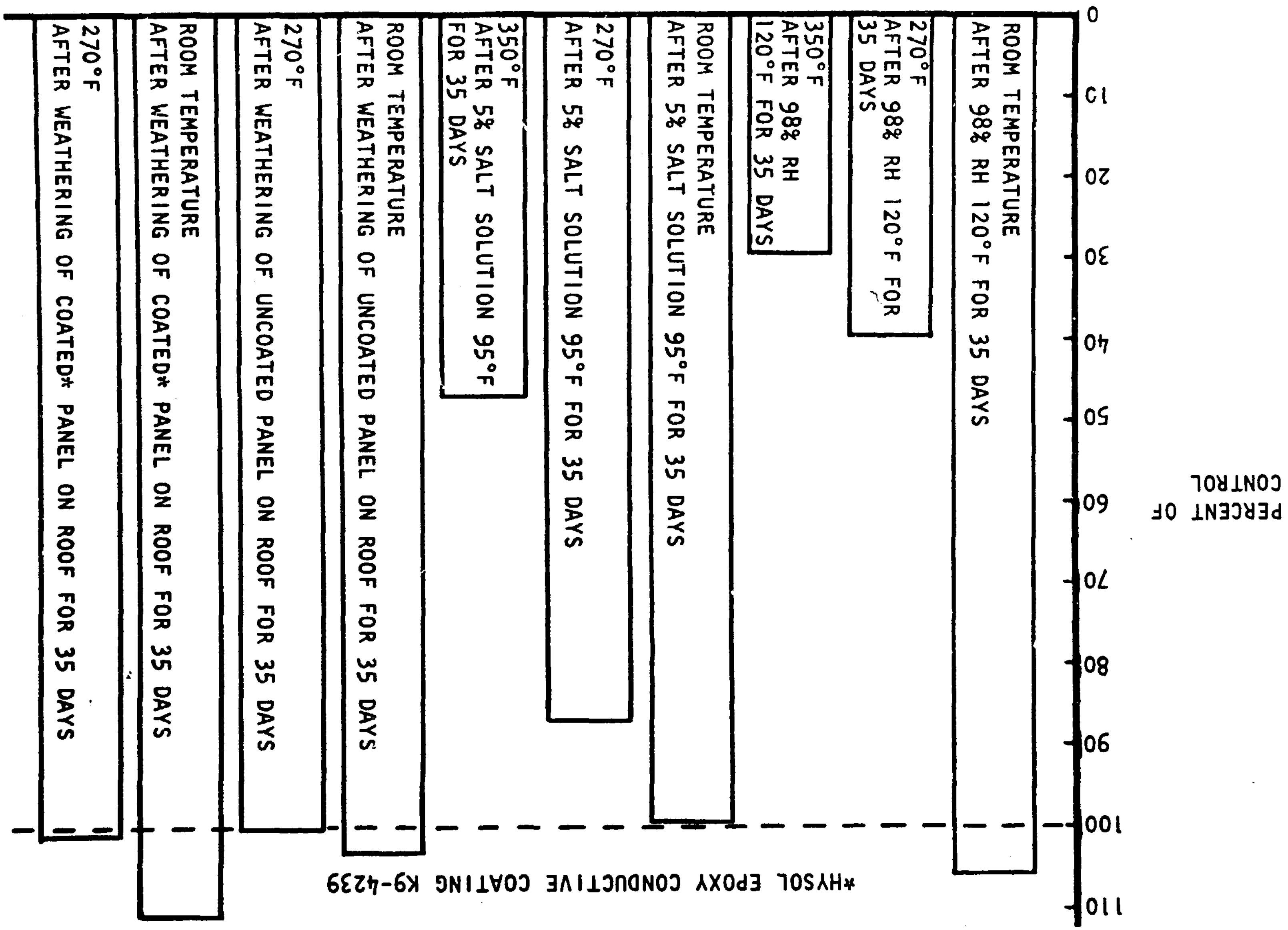
TABLE LXXV. ENVIRONMENTAL EFFECTS DATA - HUMIDITY, SALT SPRAY, AND WEATHERING - GRAPHITE/EPOXY TYPE AS/3002 BATCH

	Prior Exposure		Humidity		Salt Spray		Weathering			
			98% RH 120°F/35 Days		5% Salt Solution 95°F/35 Days		Uncoated on Roof/35 Days		Coated** on Roof/35 Days	
Test	Test Temp (°F)	Control Stress (Ksi)	Stress* (Ksi)	% of Control	Stress* (Ksi)	% of Control	Stress* (Ksi)	% of Control	Stress* (Ksi)	% of Control
Longitudinal flexure	RT	217.0	231.0	106	215.0	99	224.0	103	241.0	111
	270	225.0	87.2	39	195.0	87	224.0	100	227.0	101
	350	185.0	54.0	29	87.2	47	---		---	
Transverse flexure	RT	14.2	3.40	24	9.15	64	---		---	
	270	8.65	2.82	33	5.62	65	---		---	
	350	2.79	2.47	88	3.84	138	---		---	
Inter-laminar shear	RT	18.0	11.7	65	15.5	86	17.8	99	18.0	100
	270	10.8	4.69	43	7.24	67	10.5	97	10.7	99
	350	8.56	2.70	32	5.10	60	---		---	

*Average of three specimens

**Coated with Hysol Epoxy Conductive Coating K9-4239, Hardener H2-3487

Figure 198. Longitudinal Flexure Strengths for Unidirectional Laminates Previously Exposed to Humidity, Salt Spray, or Weathering - Type AS/3002 Batch Graphite/Epoxy



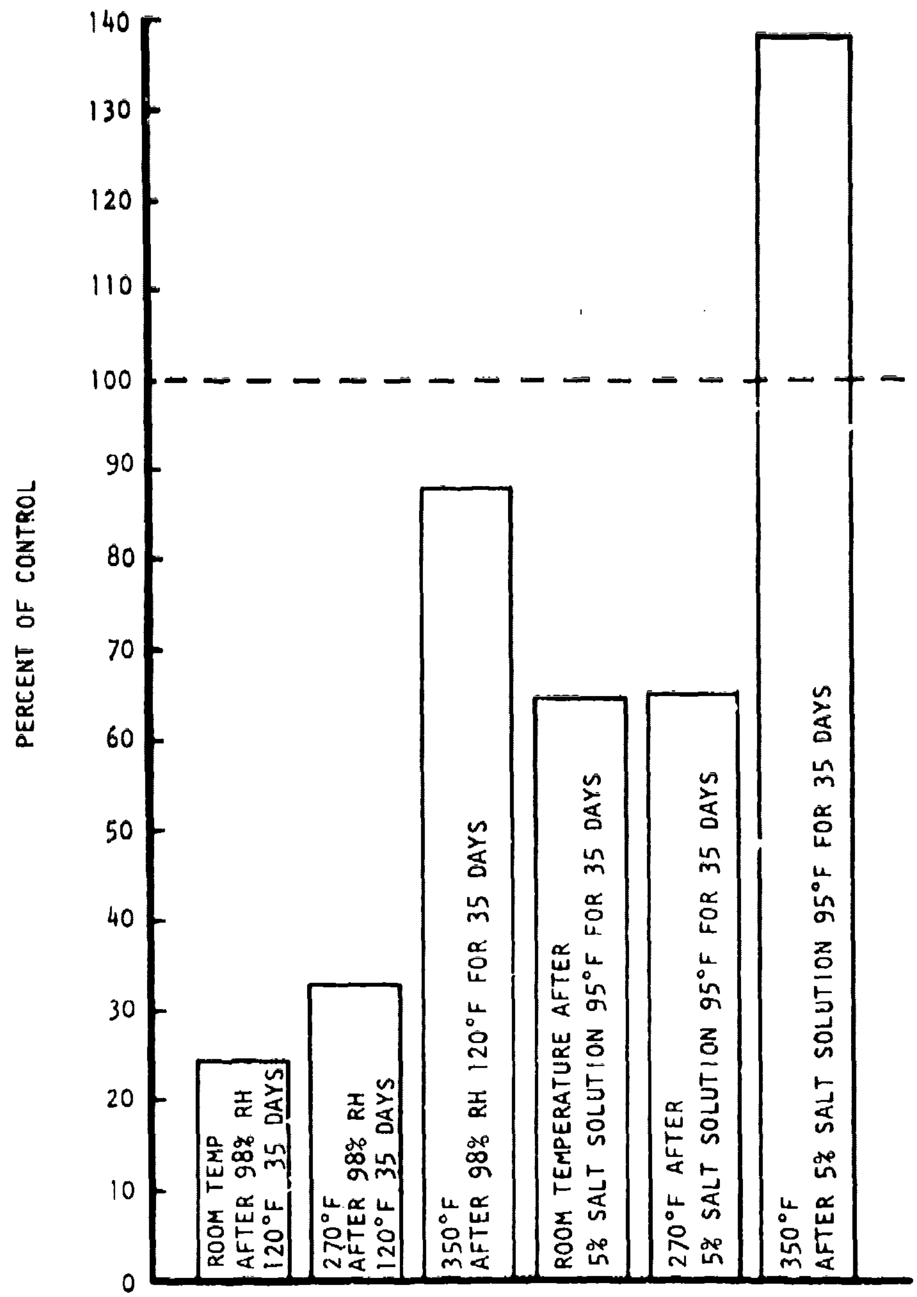
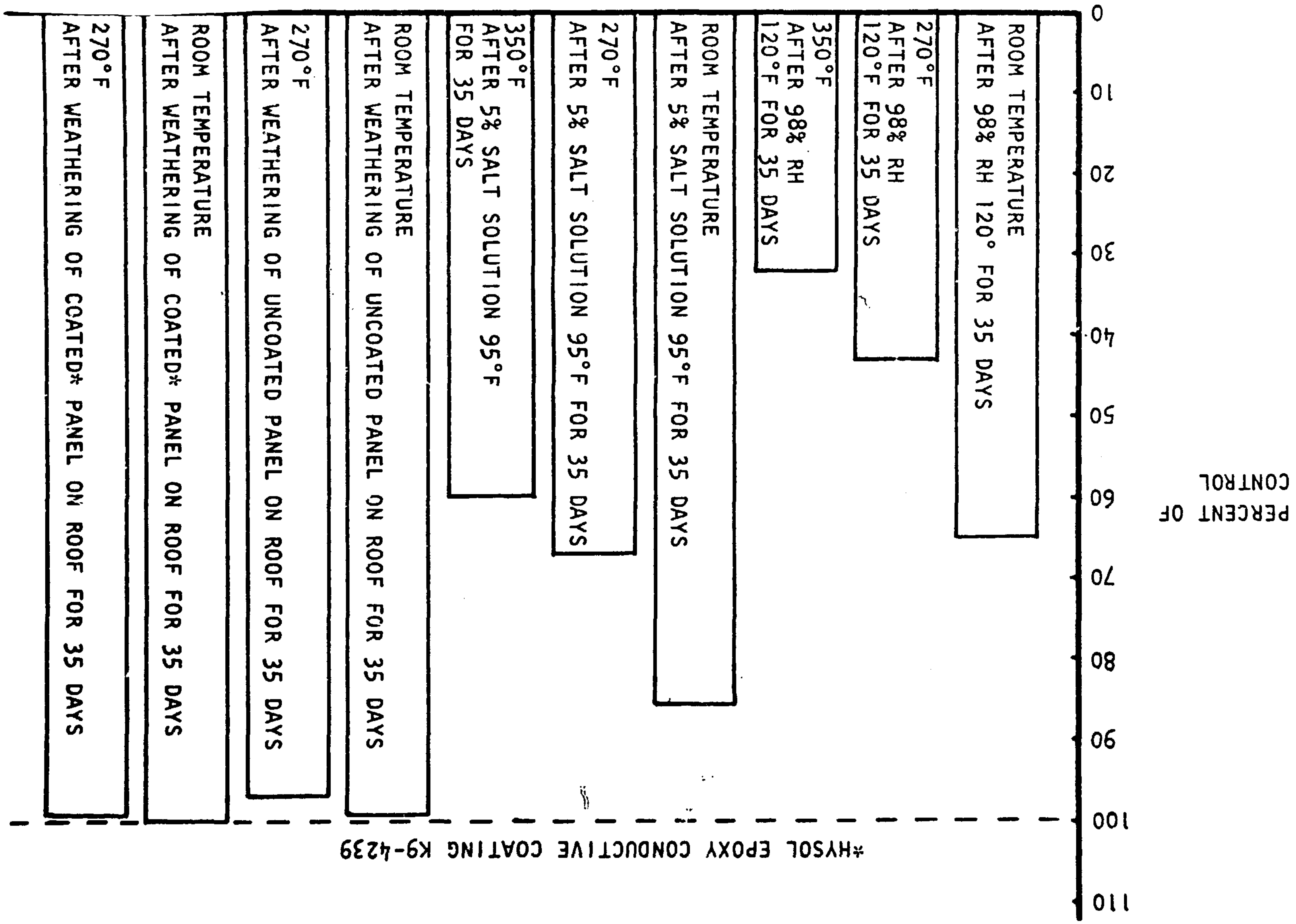


Figure 199. Transverse Flexure Strengths for Unidirectional Laminates Previously Exposed to Humidity, Salt Spray, or Weathering-Type AS/3002 Batch Graphite/Epoxy

Figure 200. Interlaminar Shear Strengths for Unidirectional Laminates Previously Exposed to Humidity, Salt Spray, or Weathering - Type AS/3002 Batch Graphite/Epoxy



Fluids - Permeability

Fuel permeability studies were conducted on graphite/epoxy laminate material of two thicknesses ($[0]_9$ and $[0]_{16}$), utilizing the test chamber assembly shown in figure 201. Prior to insertion into this chamber (bag side to fuel), each laminate test disc was weighed. The chamber was then filled with JP4 fuel containing a red dye, and capped and sealed. Each filled fuel chamber assembly was then pressurized to 10 psig, a typical fuel tank requirement, and allowed to stand for 17 days under ambient conditions. The individual laminate test discs were removed, wiped dry of any fuel and were reweighed.

During this 17-day pressurized fuel environment, no evidence of fuel penetration through the laminate thickness was detected. The fuel absorption results are presented in table LXXVI. The specific weight gain of the graphite/epoxy laminate test specimens appears to be in close agreement with their corresponding aluminum control discs, with the exception of the two previously sanded laminate discs noted in the table. The outer periphery of these specimens had been sanded as a surface preparation for utilizing a bonded permeability fixture, rather than the fixture actually used. Consequently, this surface conditon, one in which the continuous matrix resin seal has been removed, provided access to the fiber-matrix interface and was relatively more absorbent than the nonsanded specimens. In conclusion, based specifically on the test conditions and exposure time previously noted, graphite/epoxy composite laminates have permeability characteristics comparable with metal as a fuel barrier.

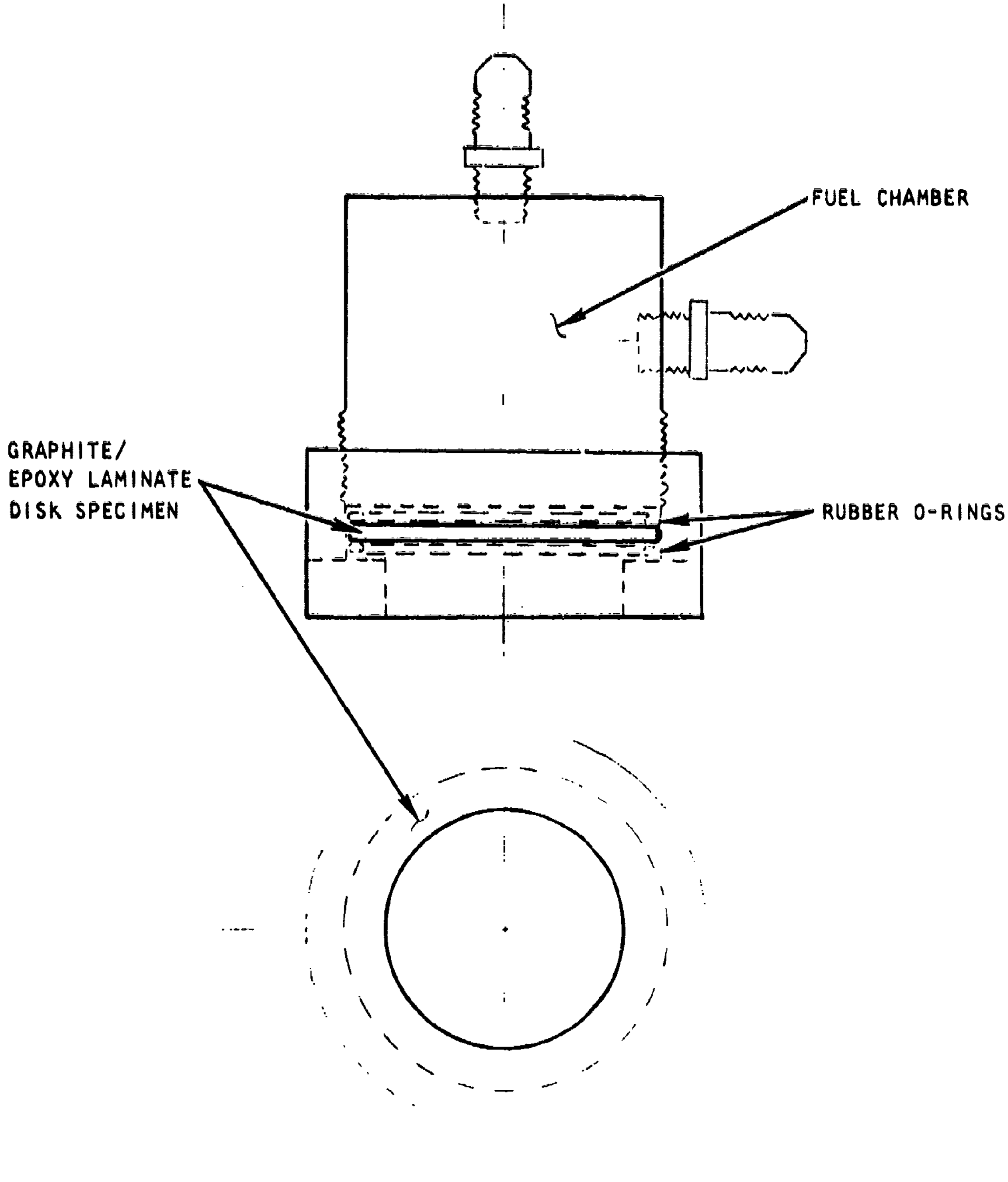


Figure 201. Fuel Permeability Test Chamber Assembly

TABLE LXXVI. FUEL PERMEABILITY DATA - GRAPHITE/EPOXY LAMINATE - TYPE AS/3002

Specimen No.	Weight Initial (gm)	Weight Final** (gm)	Weight Fuel Absorbed (gm)	Percent Weight Gain (%)
Aluminum control				
No. 1	15.4554	15.4575	0.0021	0.01
No. 2	15.6752	15.6774	0.0022	0.01
Graphite/ Epoxy [0] 9 plies				
No. 1	4.1943	4.1971	0.0028	0.07
No. 2	4.3068	4.3094	0.0026	0.06
No. 3	4.2090	4.2115	0.0025	0.06
[0] 16 plies				
No. 1	6.1404	6.1478	0.0074	0.12*
No. 2	6.2209	6.2233	0.0024	0.04
No. 3	6.1512	6.1565	0.0053	0.09*

*Specimens sanded prior to test

**Specimens under 10 psi JP-4 fuel pressure for 17 days

THERMAL AGING

Effects on Q.C. Properties

Environmental effects data for specimens which were previously subjected to thermal aging are presented in table LXXVII. Flexure and interlaminar shear strength tests were run for room, 270, 350, and -65°F temperatures. The "exposed" test values were compared to control (unexposed) values and are graphically presented in figures 202 through 204.

The following lists presents the effects observed due to thermal aging.

Environment	Effect
Thermal aging for 500 hours at 270°F	Room temperature and 270°F longitudinal flexure and interlaminar shear strengths were unaffected by 500 hours thermal aging at 270°F. The room temperature and 270°F transverse flexure strengths were both reduced to about 82% of the control values.
Thermal aging for 500 hours at 350°F	The longitudinal flexure strength was unaffected for both room temperature and 350°F. The transverse flexure strength at room temperature was 10% lower than control, while the 350°F transverse flexure strength was 269% higher than the control* value. The room-temperature interlaminar shear strength was decreased by 12%, while the 350°F strength was unaffected.

*The control value for 350°F transverse flexure strength appears to be too low, as all the exposed test values of 350°F transverse flexure strength exceeded the control value by 38 to 169%.

TABLE LXXVII. ENVIRONMENTAL EFFECTS DATA - THERMAL AGING, GRAPHITE/EPOXY TYPE AS/3002 BATCH

Test	Prior Exposure		Thermal Aging			
			270°F/500 Hours		350°F/500 Hours	
	Test Temp (°F)	Control Stress* (Ksi)	Stress* (Ksi)	% of Control	Stress* (Ksi)	% of Control
Longitudinal flexure	RT	217.0	210.0	97	233.0	107
	270	225.0	234.0	104	---	---
	350	185.0	---	---	201.0	109
Transverse flexure	RT	14.2	11.6	82	12.6	89
	270	8.65	7.06	82	---	---
	350	2.79	---	---	7.51	269**
Interlaminar shear	RT	18.0	17.9	99	15.9	88
	270	10.8	12.3	114	---	---
	350	8.56	---	---	8.80	103

*Average of three specimens
**Questionable control value

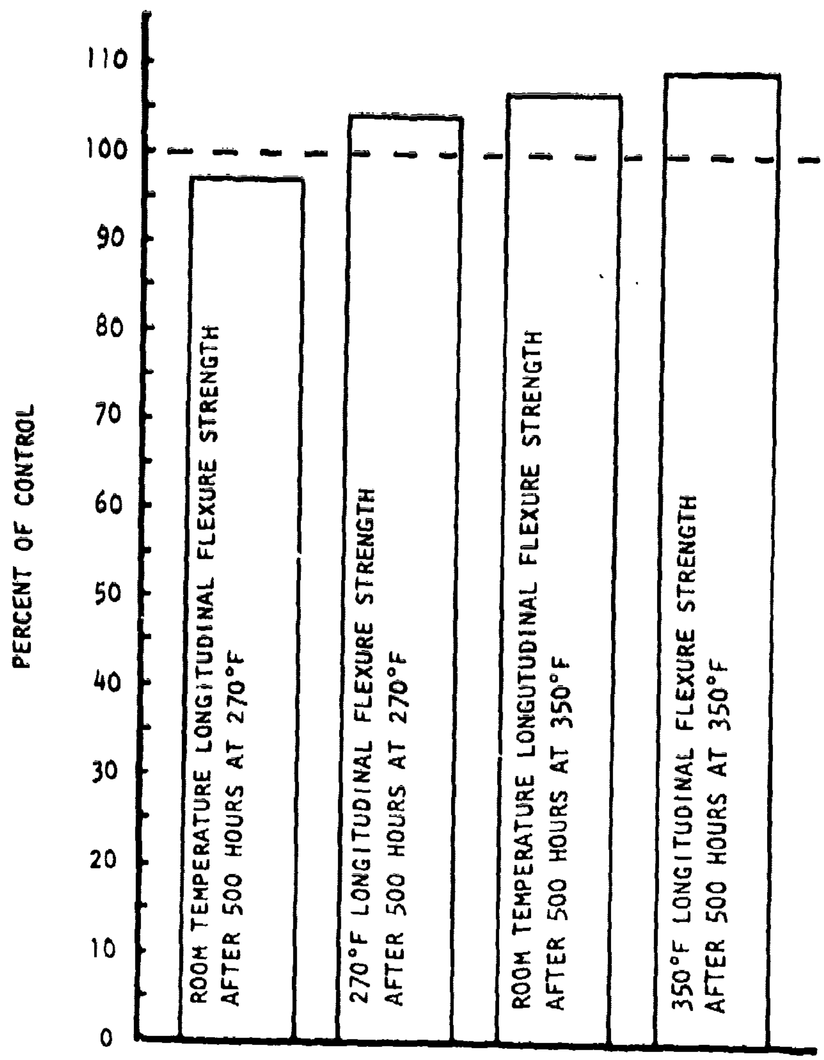


Figure 202. Room and Elevated Temperature Longitudinal Flexure Strengths After Thermal Aging - Unidirectional Type AS/3002 Batch Graphite/Epoxy

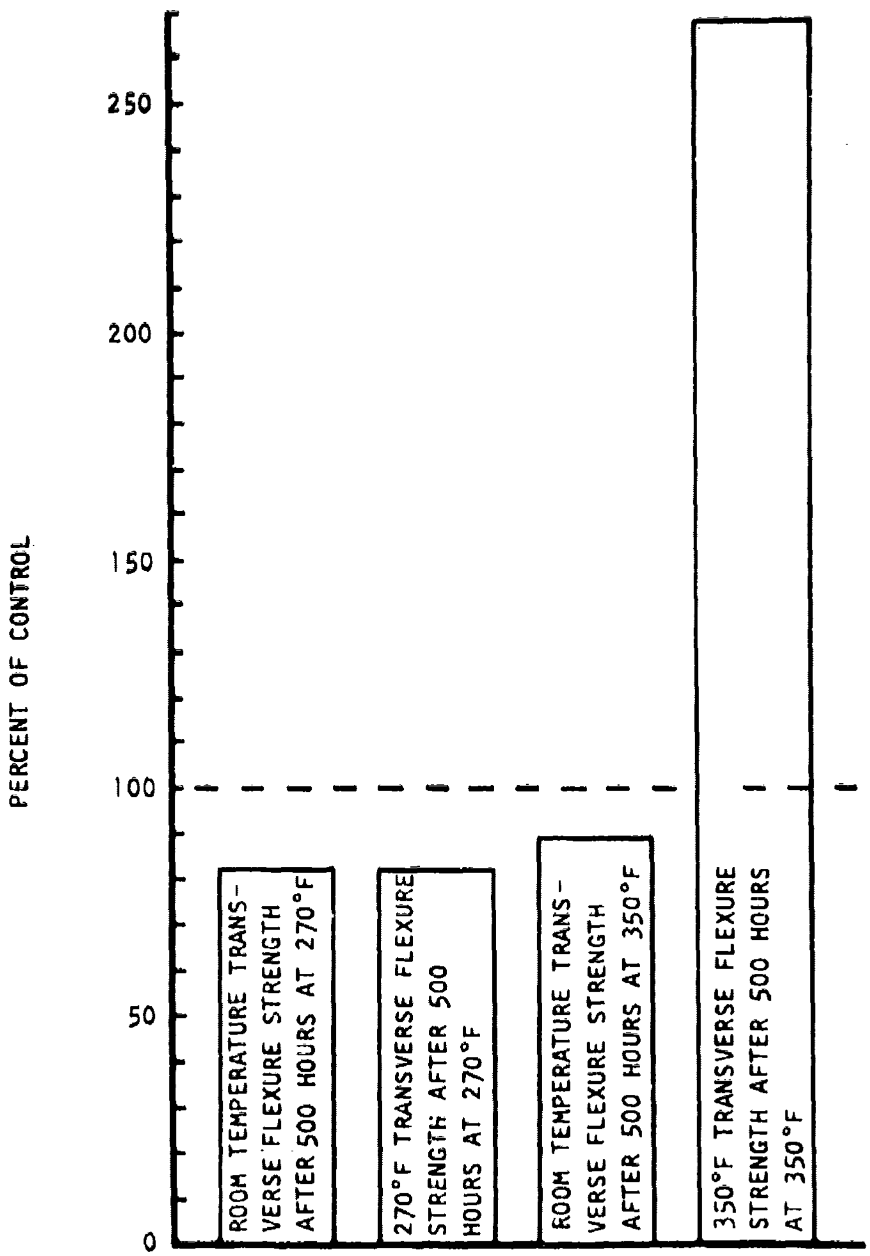


Figure 203. Room and Elevated Temperature Transverse Flexure Strengths After Thermal Aging - Unidirectional Type AS/3002 Batch Graphite/Epoxy

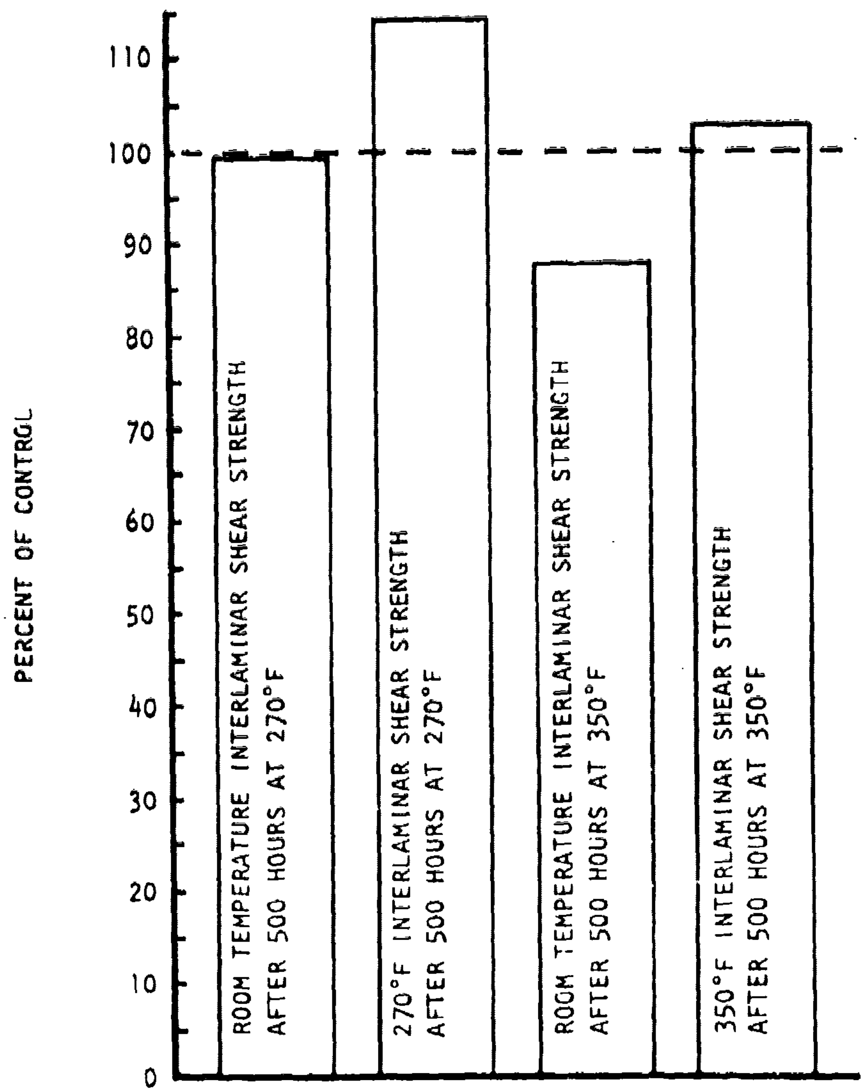


Figure 204. Room and Elevated Temperature Interlaminar Shear Strengths After Thermal Aging - Undirectional Type AS/3002 Batch Graphite/ Epoxy

AMBIENT AGING AND HUMIDITY ENVIRONMENT COMPARISON

Effect of Ambient Aging and Humidity Environment on Uncoated, Coated, and Sealed Laminate QC Properties

The effects of ambient aging and humidity environment on uncoated, coated, and sealed graphite/epoxy laminate QC properties were studied under a NR/LAD-funded IR and D program and reported in appendix III.

Appendix III, table XC, presents ambient aging data summarized for Type A/3002 - batch, untreated fiber QC data. The room-temperature tests showed no degradation, even after 6 months, for both the flexure and horizontal shear data. Elevated temperature data at 350°F, however, showed significant flexure and horizontal shear strength losses at 4 and 6 months ambient aging. An average strength loss of 43 percent for both the flexure and horizontal shear data was recorded.

Appendix III, table XCI, presents ambient and humidity environmental data for Type AS/3002 - batch, treated fiber. Tests were conducted at 300°F and showed the following trends.

1. Ambient Aging

   No significant degradation in flexure strength for ambient aging up to a period of 44 days (test date 10-6-71) for both unsealed and polyurethane coated specimens. Horizontal shear strengths showed about a 12-percent degradation for both unsealed and coated specimens, indicating that the polyurethane coating offered no protection.

2. Humidity Environment (Room Temperature at 95% Relative Humidity)

   Aluminum foil sealed specimens after 44 days showed no signficant degradation in flexure strength or horizontal shear and appear to offer a positive barrier to moisture penetration.

   Polyurethane coated specimens after 63 days showed a 15- and 29-percent strength reduction for longitudinal flexure and horizontal shear, respectively.

   Unsealed specimens after 63 days showed an 8- and 33-percent strength reduction for longitudinal flexure and horizontal shear, respectively.

Effect on Tension, Compression, and Shear Properties

Appendix III, tables XCII, XCIII, and XCIV, present 6 months ambient aging data on unidirectional and crossplied [0/$\pm$45/90] laminates for tension (IITRI coupon), compression (sandwich beam), and in-plane shear (rail shear), respectively. Tests were conducted at room temperature and 265°F, and the results showed that there was no degradations in strength from control data values at either test temperature.

THERMAL - PHYSICAL CONSTANTS

Coefficient of Thermal Expansion

Unidirectional Laminates

Coefficient of thermal expansion was determined for unidirectional Type AS/3002 - batch, graphite/epoxy laminates, using methods described in ASTM Method E228 ("Linear Thermal Expansion of Rigid Solids with a Vitreous Silica Dilatometer"). Each specimen was first tested at low temperature (RT to -65°F) and then at high temperature (RT to 360°F). The low-temperature tests were run in a Vycor-tube dilatometer with a helium atmosphere, while the high-temperature tests utilized a fused quartz dilatometer with a nitrogen purge. Test data are summarized in table LXXVIII and graphically shown in figure 210. The average coefficient of thermal expansion values obtained were $\alpha = 17.4 \times 10^{-6}$ in./in.°F and $\alpha = 0.49 \times 10^{-6}$ in./in./°F for the transverse and longitudinal directions, respectively; for unidirectional Type AS/3002 - batch (treated) graphite/epoxy laminates over the temperature range, room temperature to 360°F.

Similarly, the untreated Type A/3002 - batch material presented in table LXXIX had transverse and longitudinal coefficients of thermal expansion of 17.6×10^{-6} and 0.42×10^{-6} in./in./°F (average values over range room temperature to 360°F).

The room-temperature to -65°F coefficients of thermal expansion data for Type AS/3002 (treated) and Type A/3002 (untreated) graphite/epoxy both had values in the transverse direction of 13.3×10^{-6} in./in./°F. The treated Type AS/3002 in the longitudinal direction had a value of -0.18×10^{-6} in./in.-°F. Other values were obtained for a temperature range of room temperature to -305°F. These can be seen in tables LXXVIII and LXXIX.

Crossplied Laminates

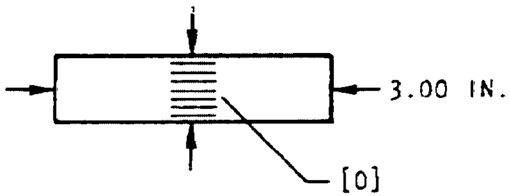
Using the previously mentioned method, the coefficient of thermal expansion data was experimentally measured for $[0/\pm45]_S$, $[90/\pm45]_S$, and $[0/\pm45/90]_S$ laminate orientations. The test data are summarized in table LXXX, and are graphically shown in figure 205.

The test values showed excellent correlation with predicted values (averaged within 9 percent of predicted), indicating that the properties of crossplied graphite/epoxy laminates of the $[0_i/\pm45_j/90_k]_S$ family can be analytically determined where the predicted values were obtained from section V.

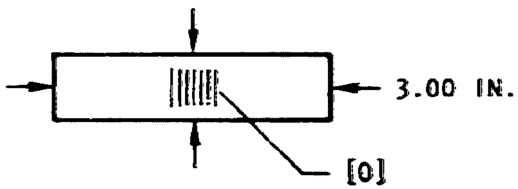
TABLE LXXVIII. TABULATION OF RESULTS FOR GRAPHITE/EPOXY
TYPE AS/3002 BATCH, COEFFICIENT OF THERMAL EXPANSION FOR UNIDIRECTIONAL LAMINATES

Specimen No.	α, μIn./In./°F	
	RT (75°F) to -65°F	RT (75°F) to 360°F
CTE-UT-1	13.3	18.1
CTE-UT-2	---	17.5
CTE-UT-3	---	18.2
CTE-UT-4	---	16.4
CTE-UT-5	13.0	16.9
Avg	(13.15)	(17.4)
CTE-UL-1	0.24*	0.59
CTE-UL-2	---	0.62
CTE-UL-3	---	0.90
CTE-UL-4	-0.18**	-0.14**
Avg	(0.03)	(0.49)

*RT (75°F) to -305°F
**Measured with duPont Thermal Analyzer - no load



CTE-UL TYPE SPECIMENS

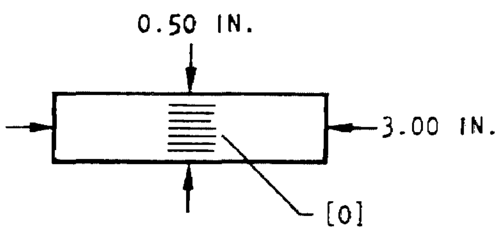


CTE-UT TYPE SPECIMENS

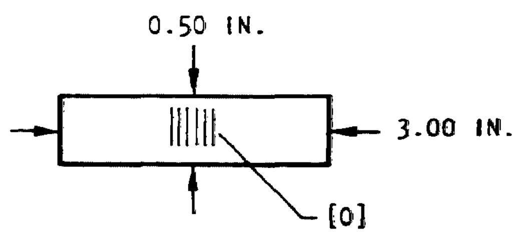
TABLE LXXIX. TABULATION OF RESULTS FOR GRAPHITE/EPOXY TYPE A/3002 BATCH - UNTREATED, COEFFICIENT OF THERMAL EXPANSION

Specimen No.	α, μ In./In./°F	
	RT (75°F) to -65°F	RT (75°F) to 360°F
CTE-UT-1	13.3	17.8
CTE-UT-2	NA	17.1
CTE-UT-3	NA	17.9
Avg		(17.6)
CTE-UL-1	0.24*	
CTE-UL-2	NA	0.28
CTE-UL-3	NA	0.56
Avg		(0.42)

*RT (75°F) to -305°F



CTE-UL TYPE SPECIMENS



CTE-UT TYPE SPECIMENS

TABLE LXXX. CROSSPLIED GRAPHITE/EPOXY - COEFFICIENT OF THERMAL EXPANSION DATA - TYPE AS/3002 BATCH

Laminate Orientation	Specimen No.	α, μ In./In./°F		αTest RT	$\frac{\alpha \text{Test}}{\alpha \text{Predicted}}$***
		RT (75°F) to -65°F Test	RT (75°F) to 350°F Test		
$[0/\pm45]_S$	CTE-24L1	---	0.38		
	CTE-24L2	---	0.17		
	CTE-24L3	0.24*(1)	0.19*		
	Avg	(0.24)	(0.25)	(0.243)	(1.35)
$[90/\pm45]_S$	CTE-24T1	4.4	4.9		
	CTE-24T3	---	4.8		
	CTE-24T3	---	5.3		
	Avg	(4.4)	(5.0)	(4.59)	(1.01)
$[0/\pm45/90]_S$	CTE-16L1	1.5**	1.7		
	CTE-16L2	---	1.9		
	CTE-16L3	---	1.9		
	Avg	(1.5)	(1.83)	(1.61)	(0.90)

*Measured with DuPont Thermal Analyzer - no load
**Range 50°F to -65°F
***Predicted value (section V)

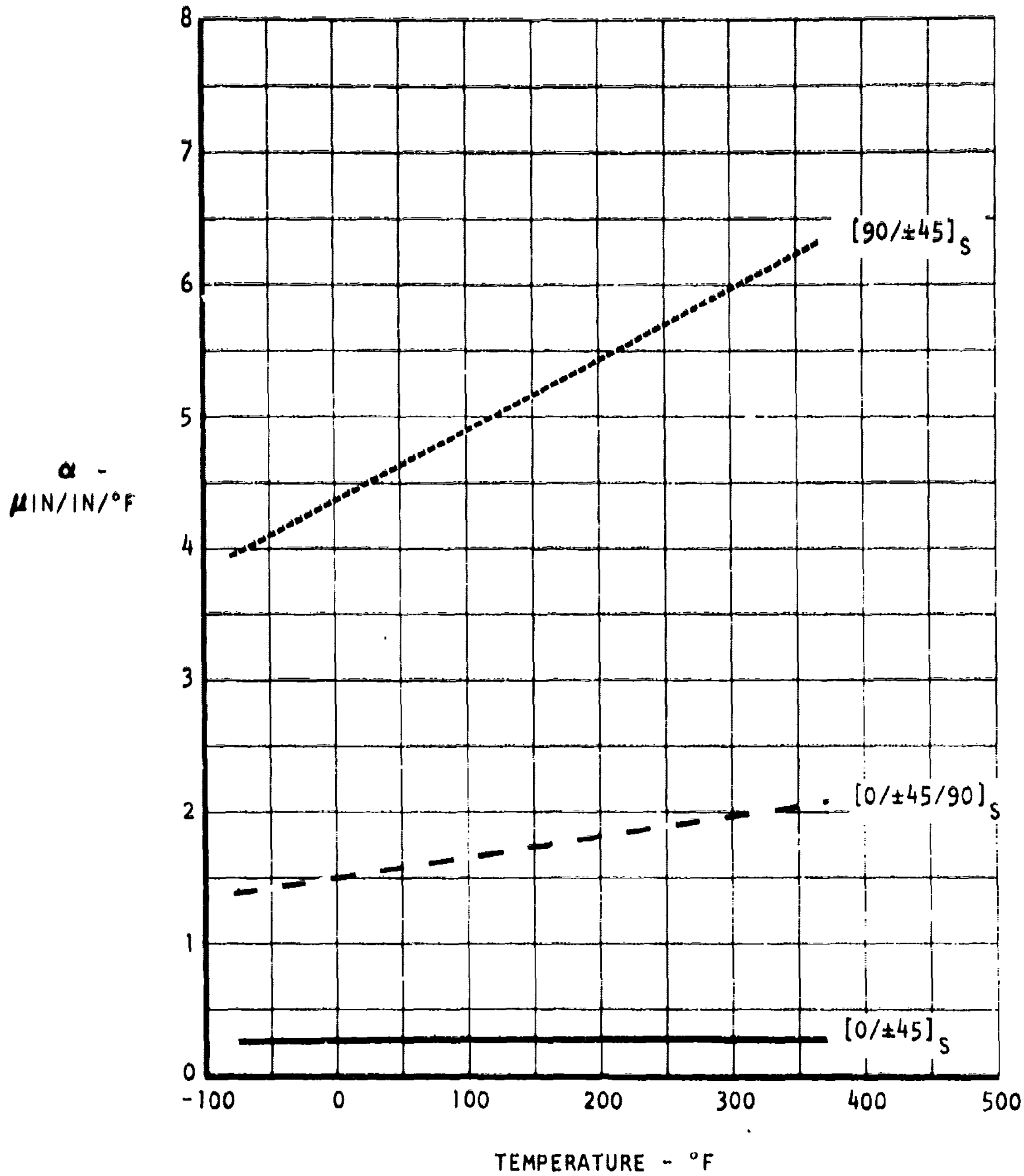


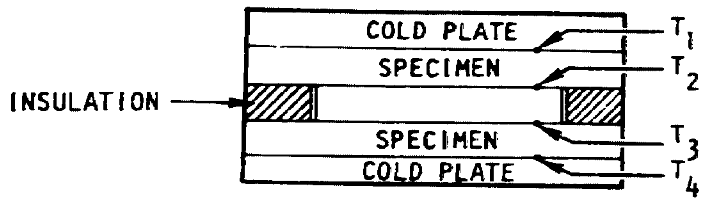
Figure 205. Crossplied Graphite/Epoxy Instantaneous Coefficient of Thermal Expansion Versus Temperature - Type AS/3002 Batch

TABLE LXXXI. THERMAL CONDUCTIVITY DATA FOR 27-PLY UNIDIRECTIONAL GRAPHITE/EPOXY LAMINATES - TYPE AS/3002 BATCH

Volts (V)	Amps (I)	Temperature (°F)						K* (BTU-ft/ft^2/hr/°F)
		T_1	T_2	T_3	T_4	ΔT	Mean Temp	
35.00	0.710	166.5	199.0	199.0	166.5	32.5	182.8	0.250
34.99	0.706	168.1	200.5	200.5	168.1	32.4	184.0	0.250
35.00	0.680	241.5	271.7	271.7	241.5	30.2	256.6	0.258
35.00	0.659	297.3	325.4	325.4	297.3	28.1	311.3	0.269
35.00	0.652	323.7	351.0	351.0	323.7	27.3	337.3	0.274
35.00	0.713	139.3	172.7	172.7	139.4	33.4	156.0	0.244
35.07	0.730	93.4	129.3	129.3	93.4	35.9	111.4	0.237
35.06	0.753	36.1	74.7	74.7	36.1	38.6	55.4	0.221
34.97	0.77	14.0	-28.5	-28.5	14.0	42.5	-7.25	0.208
34.85	0.757	-5.7	33.0	33.0	-5.7	38.7	13.7	0.223
18.90	Watts	-48.3	-12.7	-12.7	-48.3	35.6	-30.5	0.174
26.92	Watts	-4.25	38.4	38.4	42.5	42.5	17.2	0.204

$$*K = \frac{IV}{\Delta T} \times \frac{490}{\text{Area} \times 2} \times \frac{t}{12 \text{ in./ft}} = 2.0417 \frac{IVt}{\Delta T}$$

NOTE Specimen thickness, t = 0.160 in.
Area of Plate = 10 sq in.



$$\Delta T = \frac{T_2 + T_3 - T_1 - T_4}{2}$$

Thermal Conductivity

Thermal conductivity data for 27- and 18-ply Type AS/3002 - batch unidirectional graphite/epoxy laminates, determined by the guarded hot-plate method ASTM C177 ("Thermal Conductivity of Materials by Means of the Guarded Hot-Plate - Test for"), are presented in tables LXXXI and LXXXII. Note the area of the plate was 10-square inches. See the figure in the Tables for basic test specimen configuration. The basic equation used to calculate the thermal conductivity is as follows:

$$K = 2.0417 \frac{I\ V\ t}{\Delta T}$$

where

K = thermal conductivity (BTU-FT/FT^2/HR/°F)

I = current (amps)

V = voltage (volts)

t = specimen thickness (inches)

ΔT = change in temperature from one surface of the specimen to the other (Δ°F)

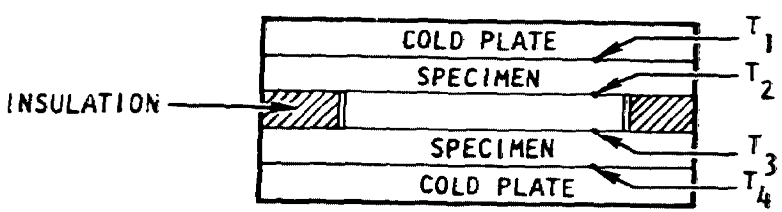
The data are also plotted in figure 206 as thermal conductivity versus mean temperature in the graphite/epoxy specimen. The basic trend exhibited was one of increasing thermal conductivity with increasing temperatures. The thermal conductivity values varied from 0.16 BTU-ft/ft^2/hr/°F at -65°F to 0.28 BTU-ft/ft^2/hr/°F at 350°F.

TABLE LXXXII.

TABLE LXXXII. THERMAL CONDUCTIVITY DATA FOR 18-PLY UNIDIRECTIONAL GRAPHITE/EPOXY LAMINATES - TYPE AS/3002 BATCH

Watts (VI)	Temperature (^{o}F)						K* ($BTU\text{-}ft/ft^2/hr/^{o}F$)
	T_1	T_2	T_3	T_4	ΔT	Mean Temp	
18.3	159.0	176.1	176.1	158.0	18.1	167.1	0.221
17.75	289.0	303.2	303.2	289.0	14.2	296.1	0.274
17.62	329.4	343.6	343.6	329.4	14.2	336.1	0.272
18.9	-60.0	-36.0	-36.0	-60.0	24.0	-48.0	0.173
19.0	-74.0	-48.0	-48.0	-74.0	26.0	-61.0	0.160
19.0	-88.5	-65.5	-65.5	-88.5	23.0	-77.0	0.181
18.8	-41.0	-16.0	-16.0	-41.0	25.0	-28.5	0.165
18.7	+41.5	60.5	60.5	+41.5	19.0	56.0	0.216

$$*K = \frac{IV}{\Delta T} \times \frac{490}{\text{Area} \times 2} \times \frac{t}{12\ \text{in./ft}} = 2.0417\ \frac{IVt}{\Delta T}$$



NOTE: Specimen thickness, t = 0.107 in.
Area of plate = 10 sq in.

$$\Delta T = \frac{T_2 + T_3 - T_1 - T_4}{2}$$

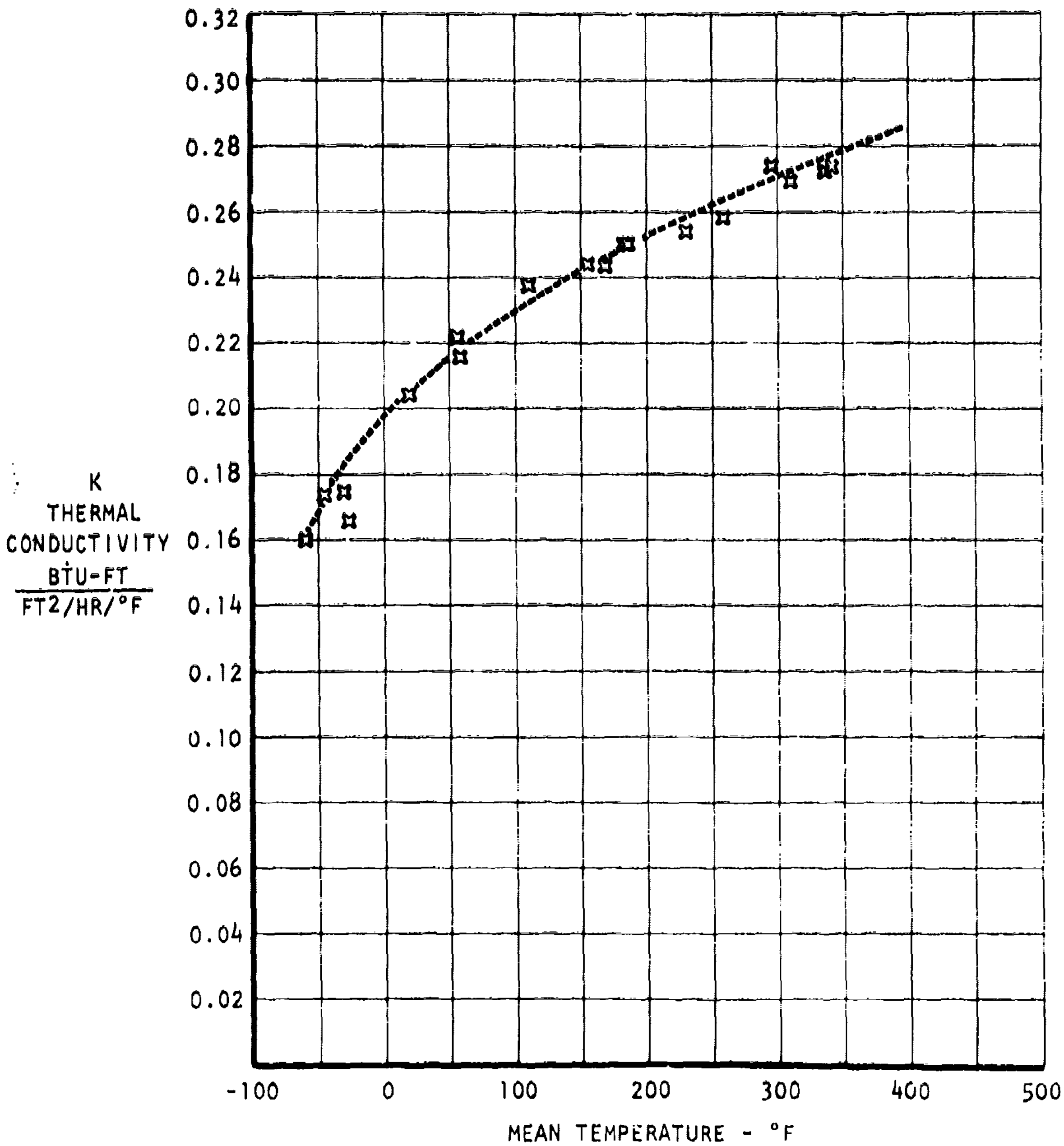
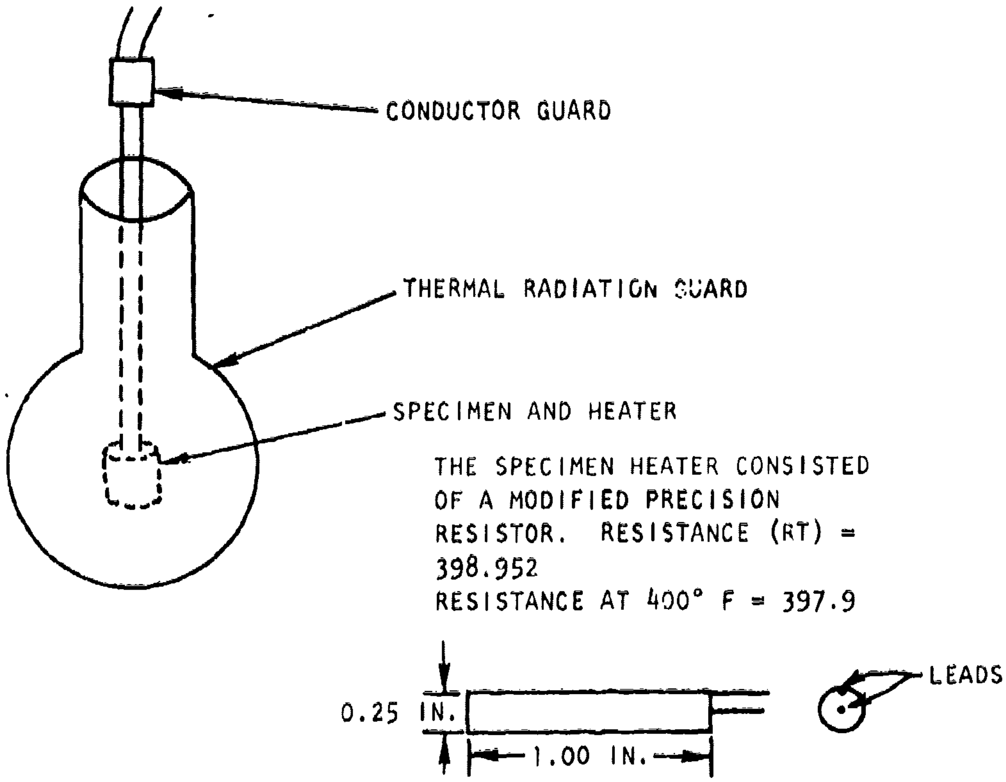


Figure 206. Thermal Conductivity Versus Mean Temperature in Specimen - (Unidirectional Graphite/Epoxy Type AS/3002 Batch)

Specific Heat

The specific heat test set up is shown below.



The thermal radiation guard consisted of an inner surface of gold, followed by a 10-mil copper layer, with the outer ply spirally wound insulated wire. The specimen consisted of a 1.0-inch-long tube, with a 0.25-inch inner diameter and a 0.50-inch outer diameter. The heater was placed in the center cavity of the specimen. Finally, thermocouple were placed on the inner surface of the radiation guard, the outer surface of the specimen, and on the conductor guard surface.

The specific heat was measured by applying a known electromotive force (voltage) to the specimen heater (resistor) for a given period of time, and by use of the specimen thermocouple measuring the change in temperature. The specific heat then was calculated by calculating the heat exchanged and dividing it by the temperature change and specimen weight. The units are BTU/°F/pound. The data are presented in table LXXXIII and graphically shown in figure 207, plotted versus mean temperature.

The basic trend observed was that the specific heat was fairly constant over the range from 100° to 150°F (about 0.25 BTU/°F/pound)/ then, it rose to 0.30 BTU/°F/pound at 225°F and leveled off to 0.33 BTU/°F/pound at 350°F.

TABLE LXXXIII. SPECIFIC HEAT VALUES FOR TYPE AS/3002 BATCH GRAPHITE/EPOXY AT VARIOUS TEMPERATURES

Mean Temperature (^{o}F)	Specific Heat (BTU/^{o}F/lb)
97.3	0.249
100.2	0.255
101.5	0.249
117.1	0.251
122.4	0.251
131.7	0.252
137.6	0.250
156.3	0.250
161.3	0.243
209.3	0.306
226.5	0.310
227.1	0.315
262.3	0.318
290.3	0.324
292.2	0.327
313.6	0.325
347.2	0.333
361.2	0.340
376.5	0.338

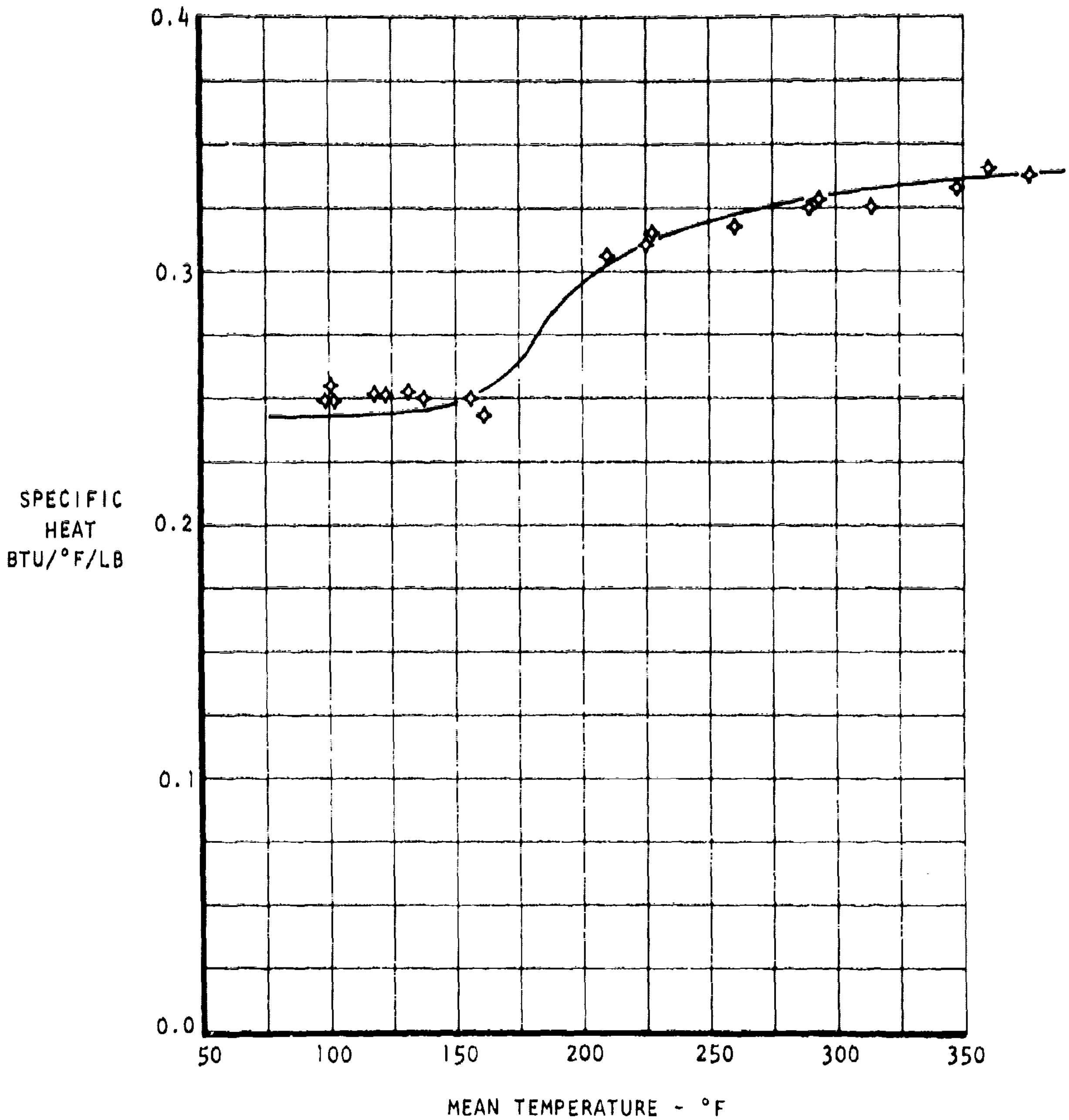


Figure 207. Specific Heat of Type AS/3002 Batch Graphite/Epoxy Versus Mean Temperature

SECTION V

DESIGN PROPERTIES

GENERAL

This section provides the basic advanced composite laminate properties for the intermediate strength graphite/epoxy system, known commercially as Type AS/3002, suitable for service environments up to 350°F. Key unidirectional and crossply laminate properties of static design strengths, elastic properties, and thermal-physical constants at room, elevated, and subzero temperatures are presented based on data from section IV and references 2, 10, and 11. Constant amplitude fatigue data for plain and holed specimens are summarized for some basic laminate orientations to provide design guidelines. Bonded single lap and double scarf joint design strengths as well as "flush head" (100° countersunk) and "protruding head" (hex head) mechanically fastened joint static and fatigue strengths are summarized. Configuration data presented in section IV provided information concerning the following:

1. Compression wrinkling strengths of laminated sandwich construction as a function of core density.

2. Strengths of single stage versus secondary bonded honeycomb structures.

3. Influence of open holes (cutouts) on basic material strengths.

4. Material allowables at thickness buildups.

This configuration data is summarized herein as design guide information.

A summary of the effects of environmental conditions on basic laminate strengths are presented which augment the baseline design properties.

STATIC PROPERTIES-BASIC LAMINATE

UNIDIRECTIONAL PROPERTIES

Room Temperature Properties

Basic room temperature key material properties for unidirectional Type AS/3002 graphite/epoxy laminate are summarized in table LXXXIV. The table provides the mechanical properties of strengths and elastic constants in the longitudinal and transverse directions based on the baseline unidirectional tests evaluated in section IV. In addition, the key thermal-physical properties of thermal coefficient of expansion in the longitudinal and transverse directions are presented. The properties are based on a nominal fiber volume fraction (V_f) of 0.60.

TABLE LXXXIV. UNIDIRECTIONAL GRAPHITE/EPOXY - TYPE AS/3002 - KEY ROOM-TEMPERATURE MATERIAL PROPERTIES

Design Strengths*	Longitudinal Tensile Ultimate - F_L^{tu} (Ksi)	160
	Transverse Tensile Ultimate - F_T^{tu} (Ksi)	7.5
	Longitudinal Compression Ultimate - F_L^{cu} (Ksi)	160
	Transverse Compression Ultimate - F_T^{cu} (Ksi)	25
	In-Plane Shear Ultimate - F_{LT}^{su} (Ksi)	10
	Interlaminar Shear Ultimate - F^{isu} (Ksi)	13
	Ultimate Longitudinal Strain - ϵ_L^{tu} (μ in./in.)	9,500
	Ultimate Transverse Strain - ϵ_T^{tu} (μ in./in.)	4,500
Elastic Properties*	Longitudinal Tension Modulus - E_L^t (Msi)	17
	Transverse Tension Modulus - E_T^t (Msi)	1.7
	Longitudinal Compression Modulus - E_L^c (Msi)	17
	Transverse Compression Modulus - E_T^c (Msi)	1.7
	In-Plane Shear Modulus - G_{LT} (Msi)	0.65
	Longitudinal Poisson's Ratio - ν_{LT}^t	0.21
	Transverse Poisson's Ratio - ν_{TL}^t	0.021
Physical Constants*	Density - ρ (lb/in.^{3})	0.055
	Longitudinal Coefficient of Thermal Expansion α_L (μ in./in./°F)	0.3
	Transverse Coefficient of Thermal Expansion α_T (μ in./in./°F)	14.4
	Fiber Volume Fraction - V_f	0.60

*The design strength allowables are generally lower bound values, while the elastic and physical constants are typical or average values.

Temperature Effects

Figures 208 and 209 present the temperature strength retention and modulus retention curves, respectively, for the unidirectional laminate. The effect of temperature on laminate properties are shown as a percent of room temperature properties.

Figure 210 presents unidirectional coefficient of thermal expansion values in the longitudinal and transverse direction over the temperature range of $-65^{o}F$ through $375^{o}F$.

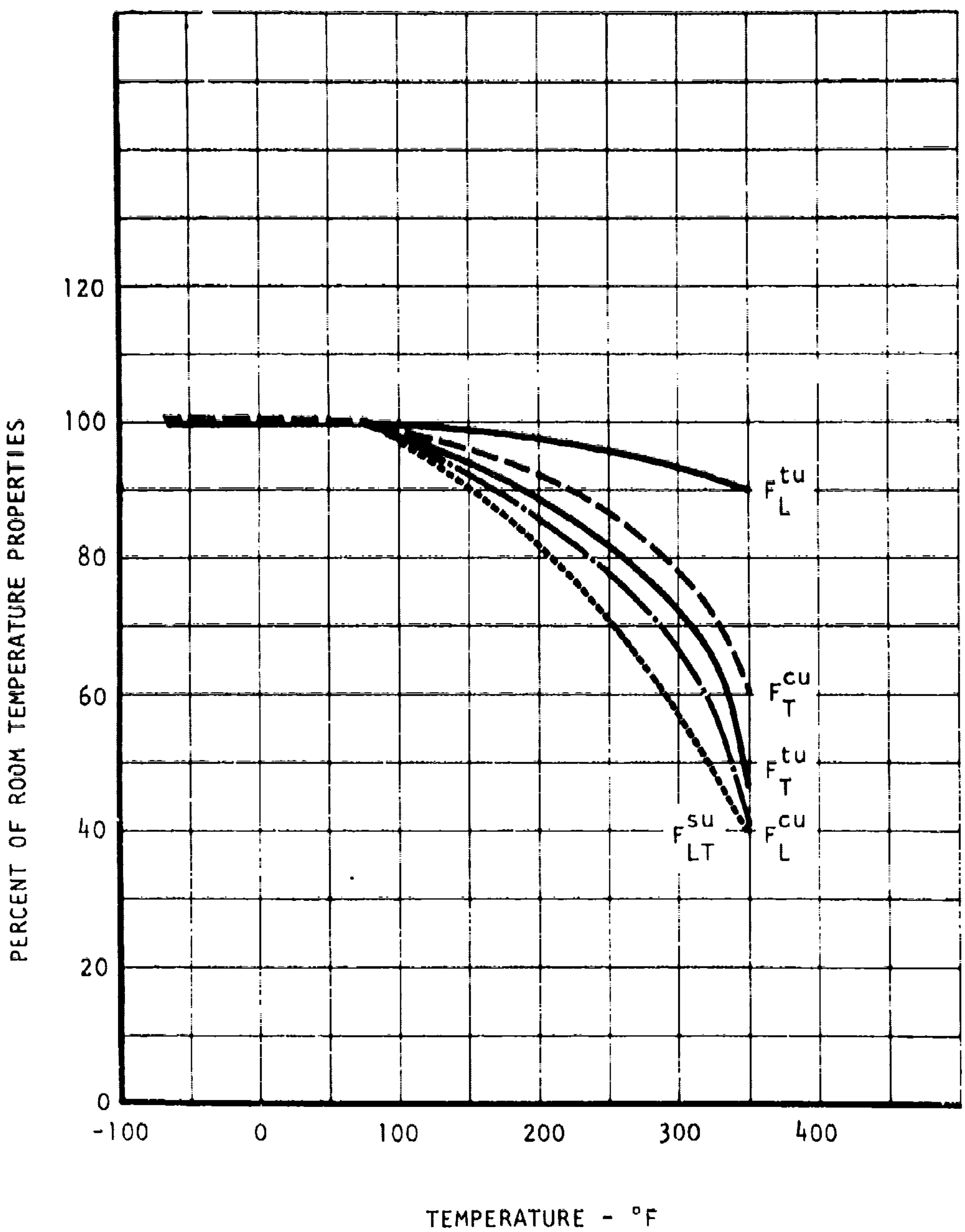


Figure 208. Strength Properties of Unidirectional Laminate at Temperature - Graphite/Epoxy - Type AS/3002

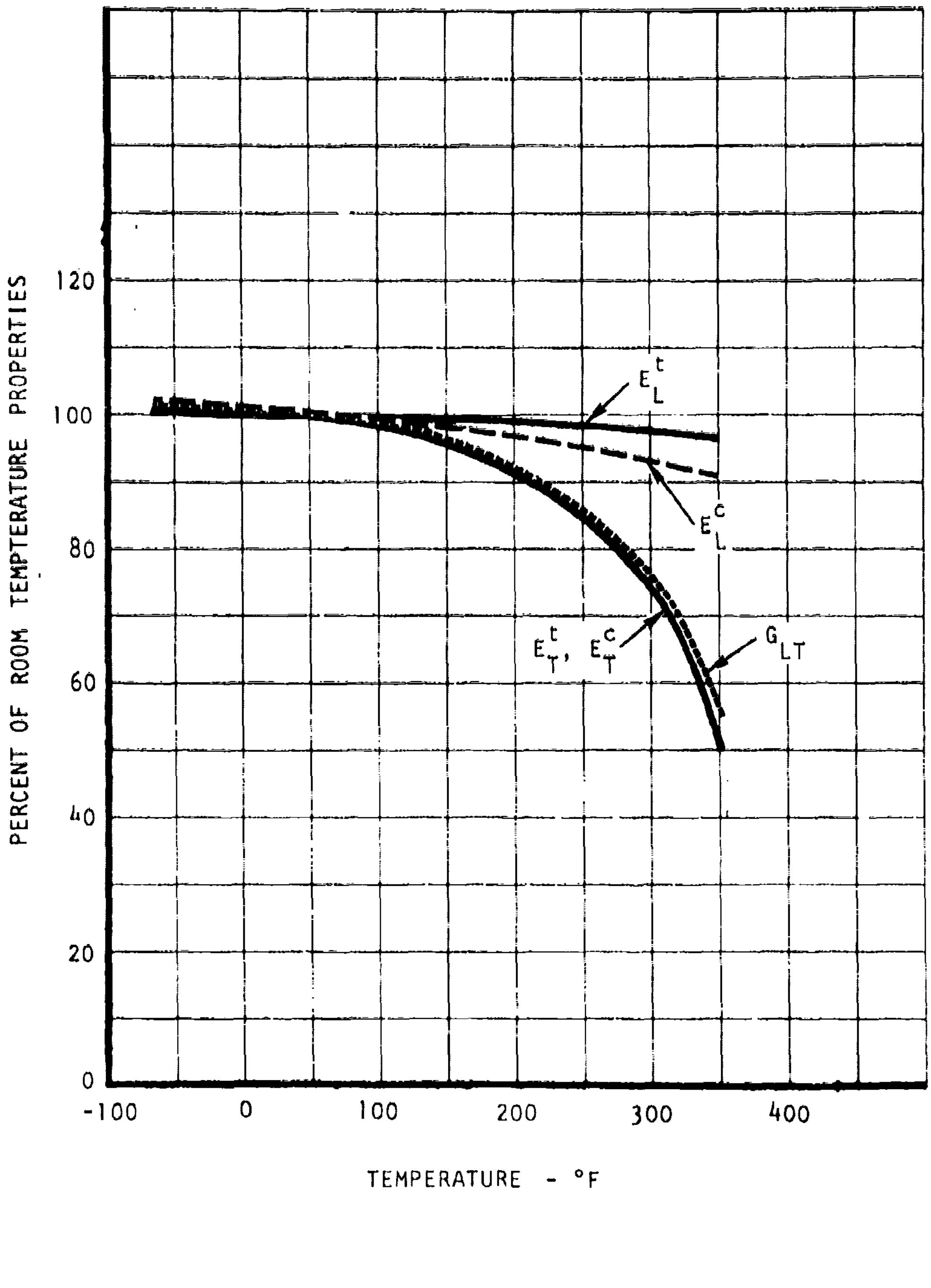


Figure 209. Elastic Properties of Unidirectional Laminate at Temperature - Graphite/Epoxy - Type AS/3002

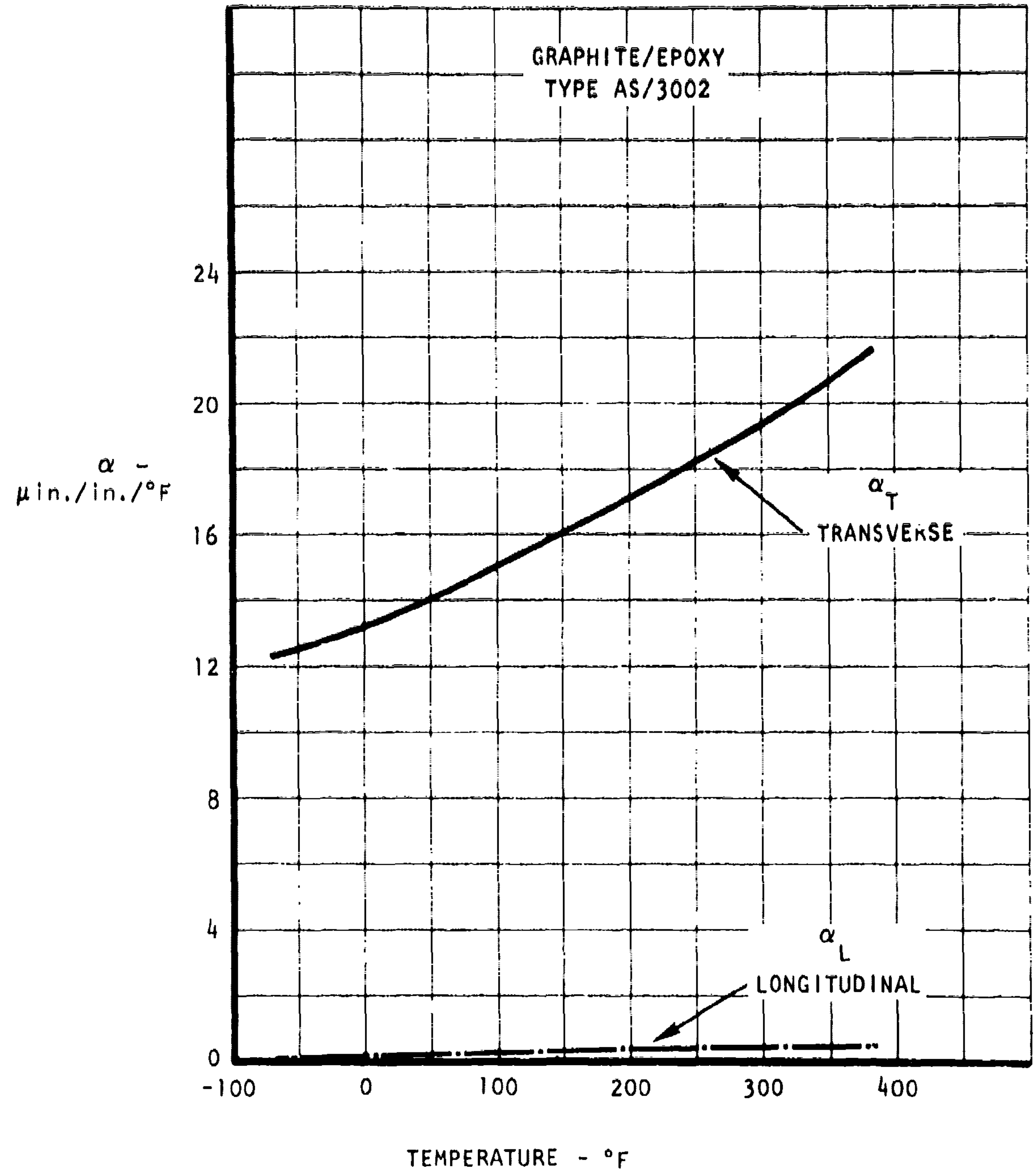


Figure 210. Instantaneous Coefficient of Thermal Expansion for Unidirectional Graphite/Epoxy - Type AS/3002

CROSSPLIED LAMINATE PROPERTIES

Crossplied laminate design strengths, elastic properties, and physical constants are presented herein for the graphite/epoxy Type AS/3002 system. The properties shown are for the general family of $[0_i/\pm45_j/90_k]$, where the i, j, k coefficients can be adjusted to any proportion of the three lamina angles, including zero percent of any of them (e.g., unidirectional [0], [±45], [0/90] are each members of this family.)

The design data in this section are generally displayed in carpet plot form, with the percent of 0^o plies and $\pm45^o$ plies as continuous variables (with the remainder at 90^o by definition). This arrangement reduces the number of figures essentially by half, since only parameters referenced to the X-axis (F_x^{tu}, E_x^t, etc) need be plotted.

Properties in the transverse direction F_y^{tu}, F_y^{cu}, E_y, α_y, can be obtained by using the percentage of 90^o plies in the laminate as the value of 0^o plies in the design curves.

Allowable Strengths

The design allowables for composite laminates are based on the use of unidirectional lamina properties and lamination theory to predict laminate strength. The strengths were developed by using the computer program "COPRM", described in reference 6. The unidirectional lamina properties from table LXXXIV are basic inputs for this program. Figures 211, 212, and 213 present the allowable tensile strength F_x^{tu} versus various percentages of $\pm45^o$ and 0^o plies for room temperature, 270^oF, and 350^oF, respectively. The allowable tension value in the transverse direction, F_y^{tu}, can be obtained by using the percentage of 90^o plies in the specific crossplied laminate as the value to use for the percent 0^o plies in the curves.

Example: $[0_2/\pm45]$ room temperature, using figure 211:

1. Use 50% ±45, 50% 0^o, $F_x^{tu} = 94$ ksi
2. Use 50% ±45, 0% 0^o, $F_y^{tu} = 24$ ksi

The strength allowable criteria utilized was based on matrix failure of the 90^o lamina where there was zero percent 0^o plies. Filament fracture were generally assumed to govern the other crossplied laminate orientations where various percentages of 0^o plies existed.

Figures 214, 215, and 216 present similar carpet plots of allowable compression strengths, F_x^{cu} for room temperature, 270^oF, and 350^oF, respectively, where generally fiber failure governed the strength level. Crossplied compression strength values were increased empirically for orientations where the percentage of ±45 was greater than 50 percent to reflect compression beam data which were significantly greater than design values of reference 2.

Figure 217 provides the design allowable shear strength, F_{xy}^{su} as a function of the percentage of ±45 plies. Curves for room temperature, 270^oF, and 350^oF are shown.

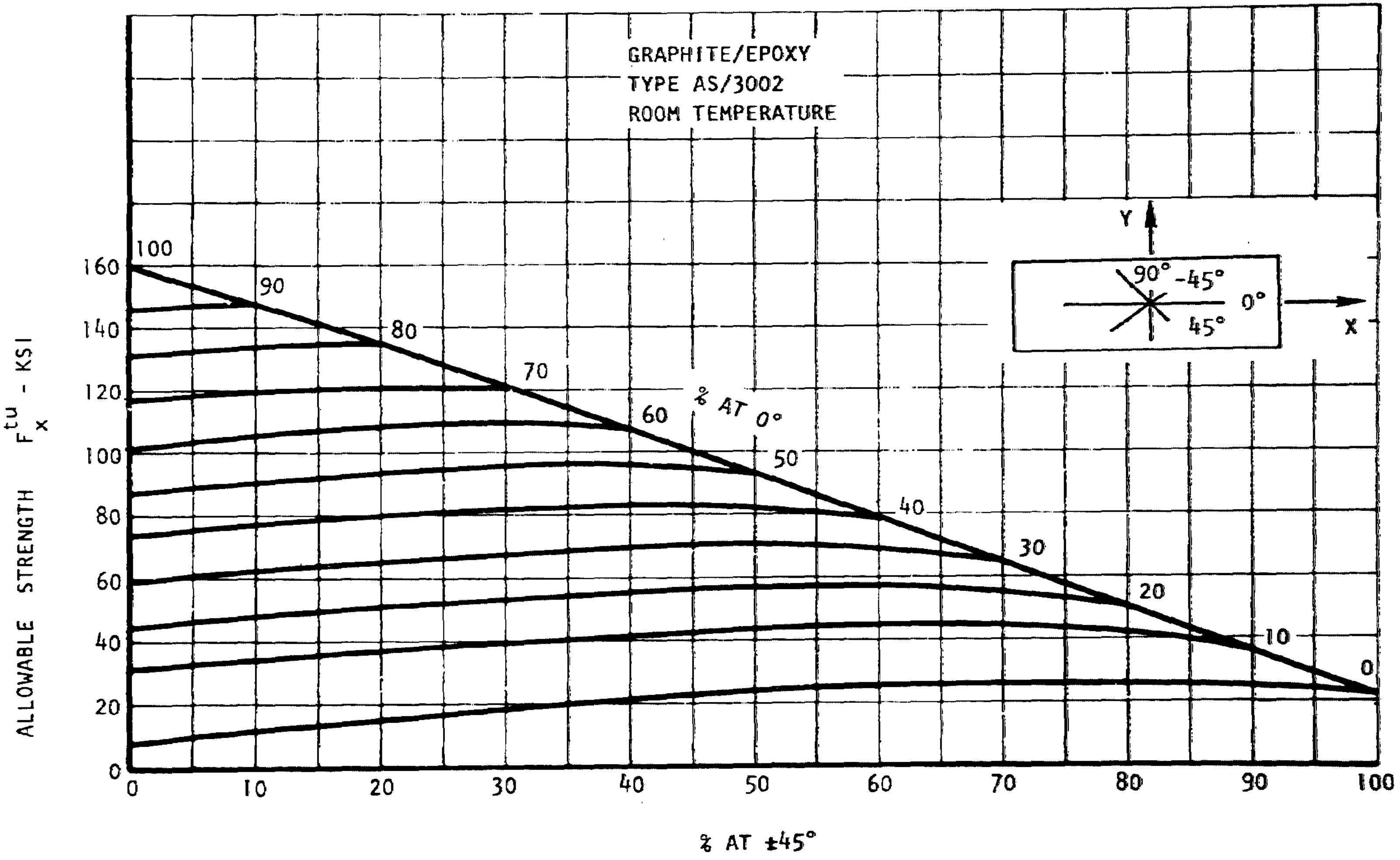


Figure 211. Laminate Ultimate Tensile Strength, F_x^{tu}, Versus Percent of Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at Room Temperature

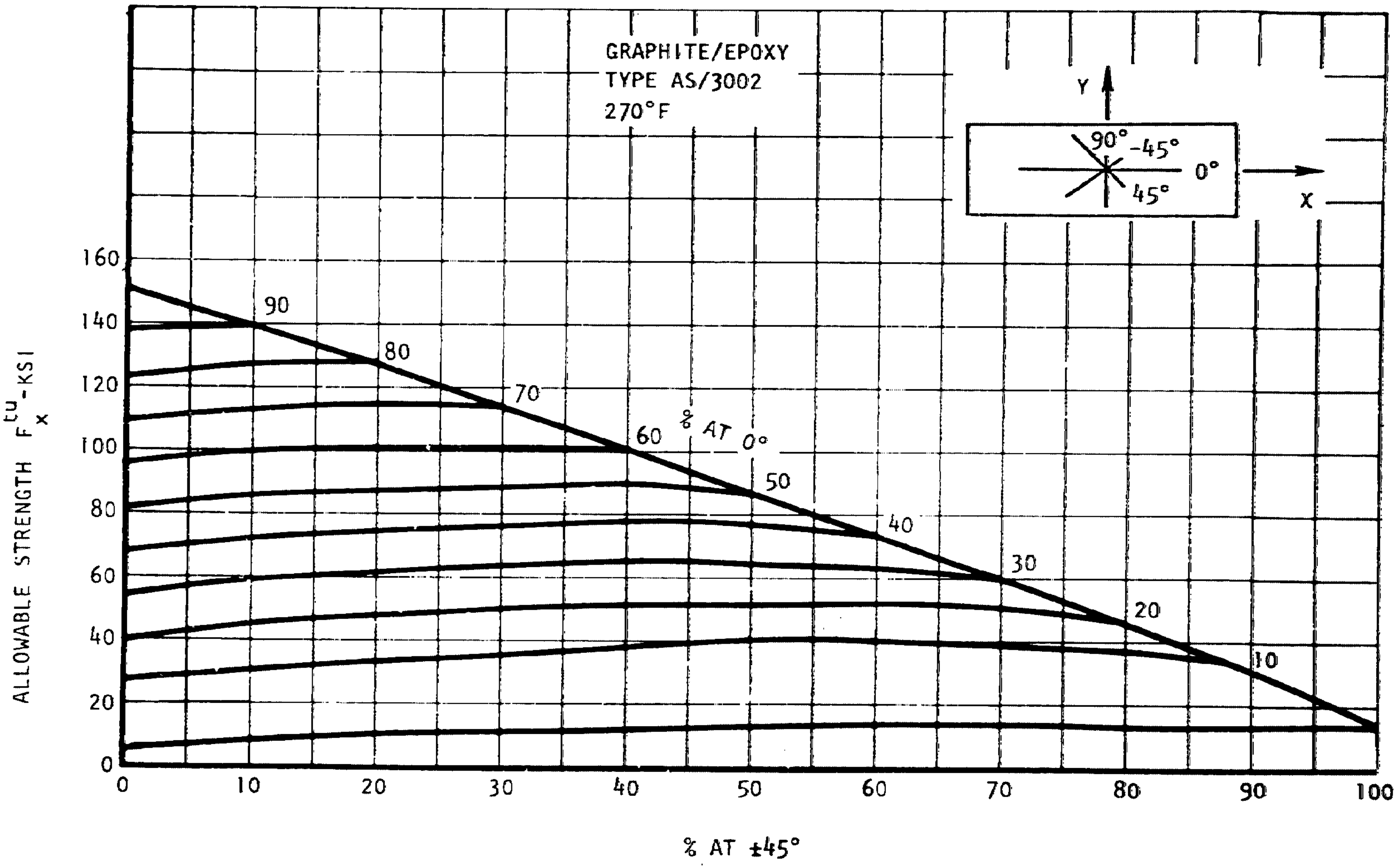


Figure 212. Laminate Ultimate Tensile Strength, F_x^{tu}, Versus Percent of Laminae, [0/±45/90] Family for Graphite/Epoxy at 270°F

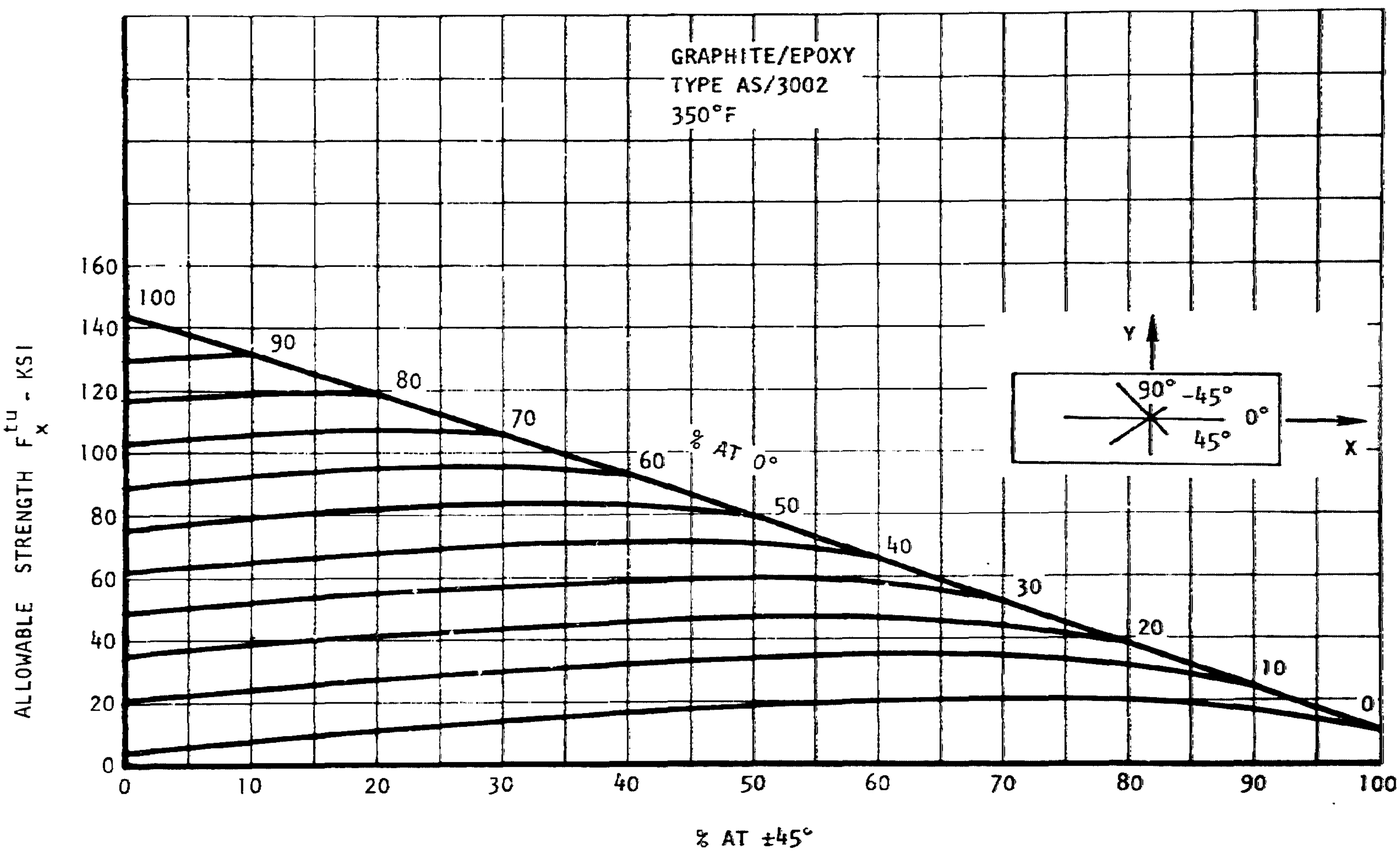


Figure 213. Laminate Ultimate Tensile Strength, F_x^{tu}, Versus Percent of Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at 350°F

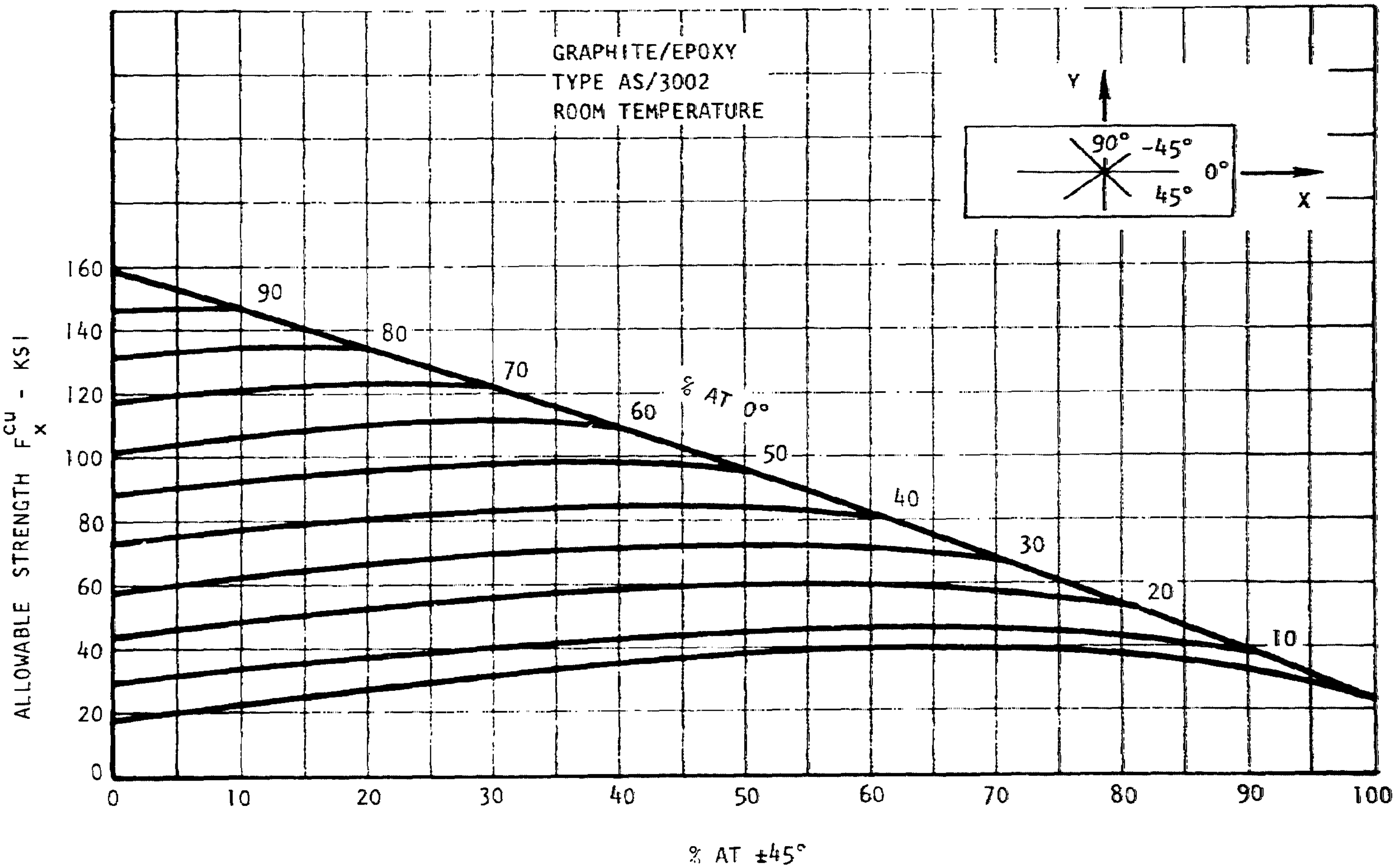


Figure 214. Laminate Ultimate Compressive Strength, F_x^{cu}, Versus Percent of Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at Room Temperature

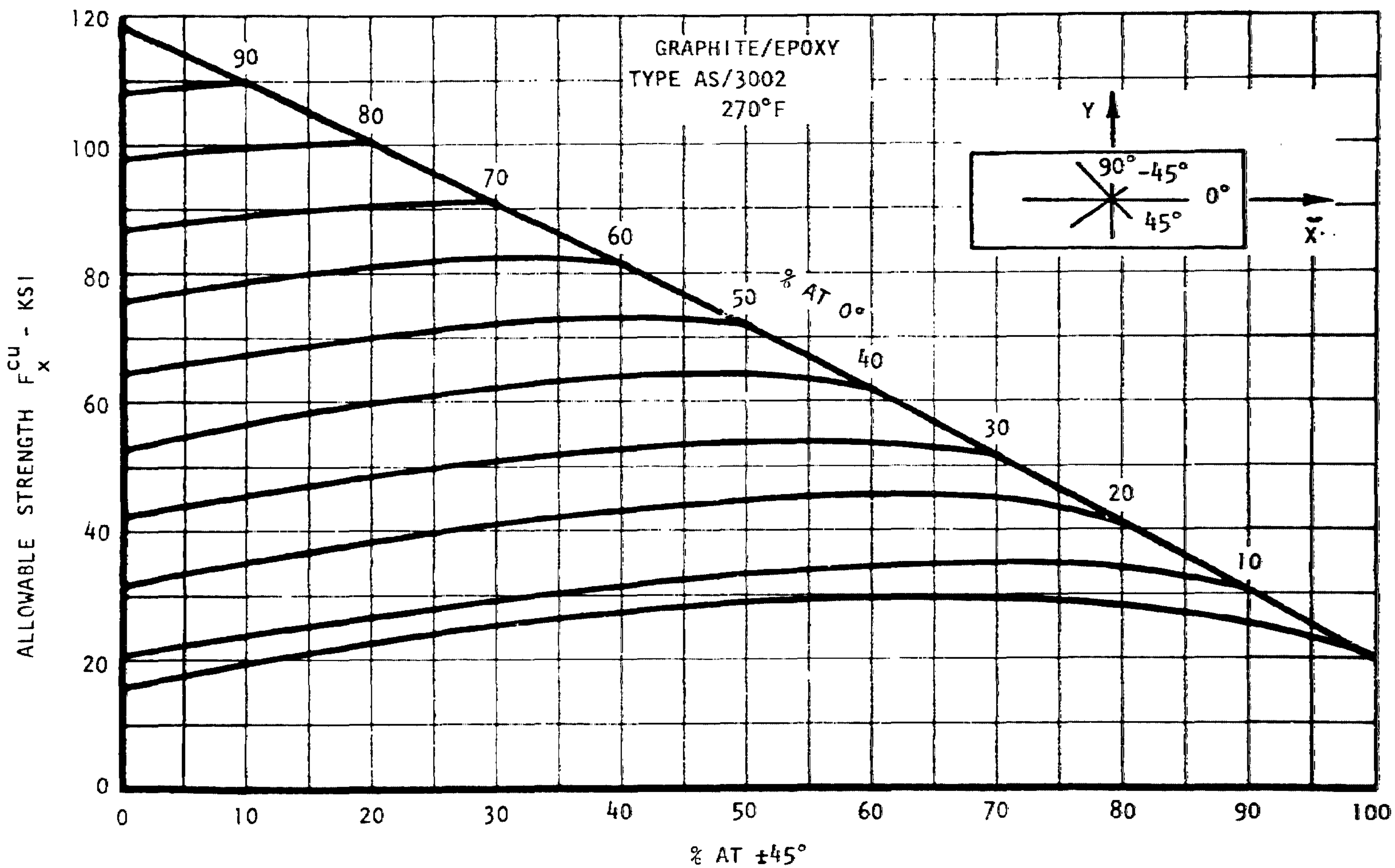


Figure 215. Laminate Ultimate Compressive Strength, F_x^{cu}, Versus Percent of Laminae, [0/±45/90] Family for Graphite/Epoxy at 270°F

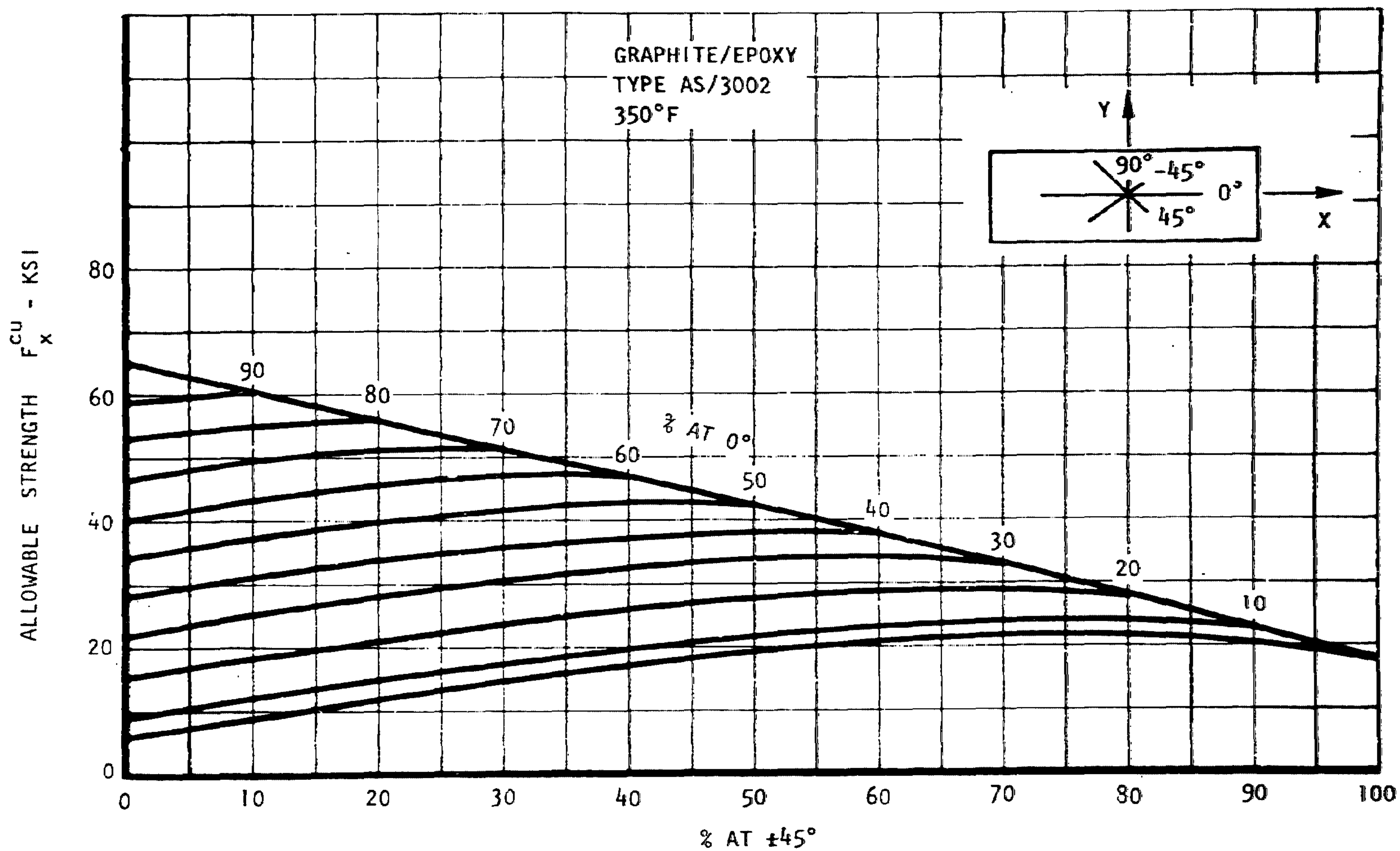


Figure 216. Laminate Ultimate Compressive Strength, F_x^{cu}, Versus Percent of Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at 350°F

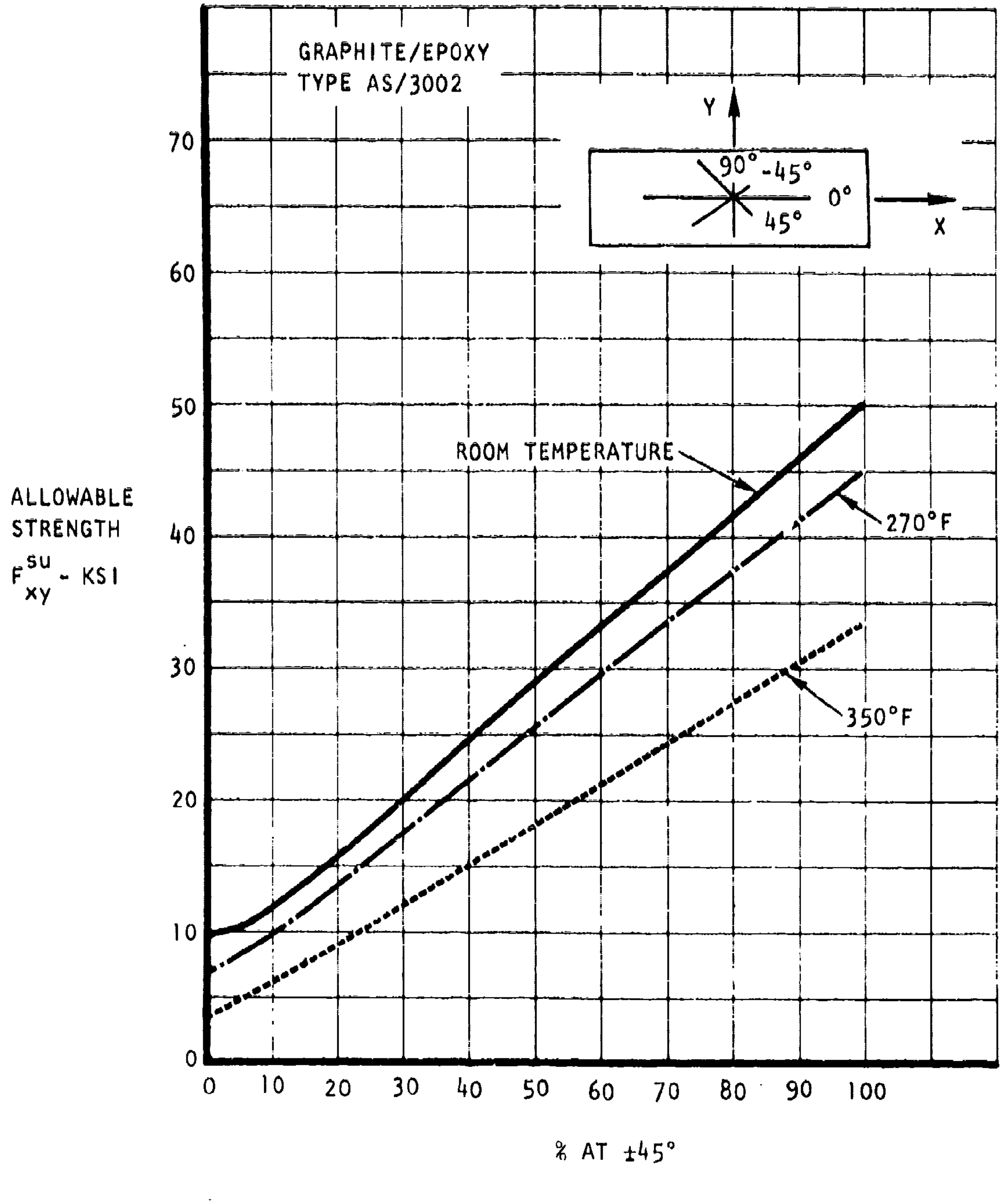


Figure 217. Laminate Ultimate Shear Strength, F_{xy}^{su}, Versus Percent of Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at Room Temperature, 270°F and 350°F

Elastic Constants

Crossply elastic property curves of E_x, G_{xy}, and ν_{xy} at room temperature, 270°F, and 350°F are presented in figures 218 through 224. These values were generated using the AC-2 computer program described in reference 3.

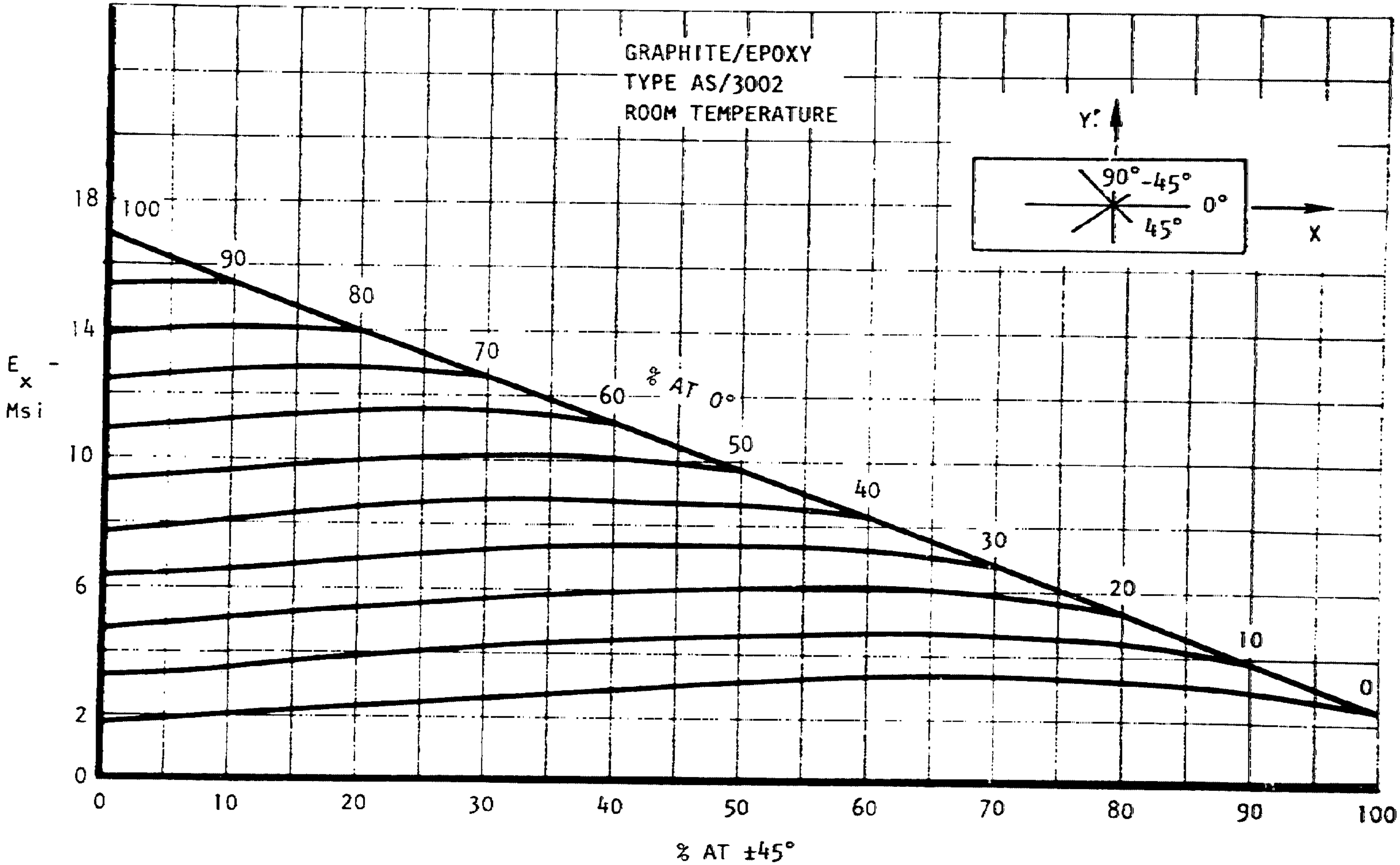


Figure 218. Laminate E_x Versus Percent Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at Room Temperature

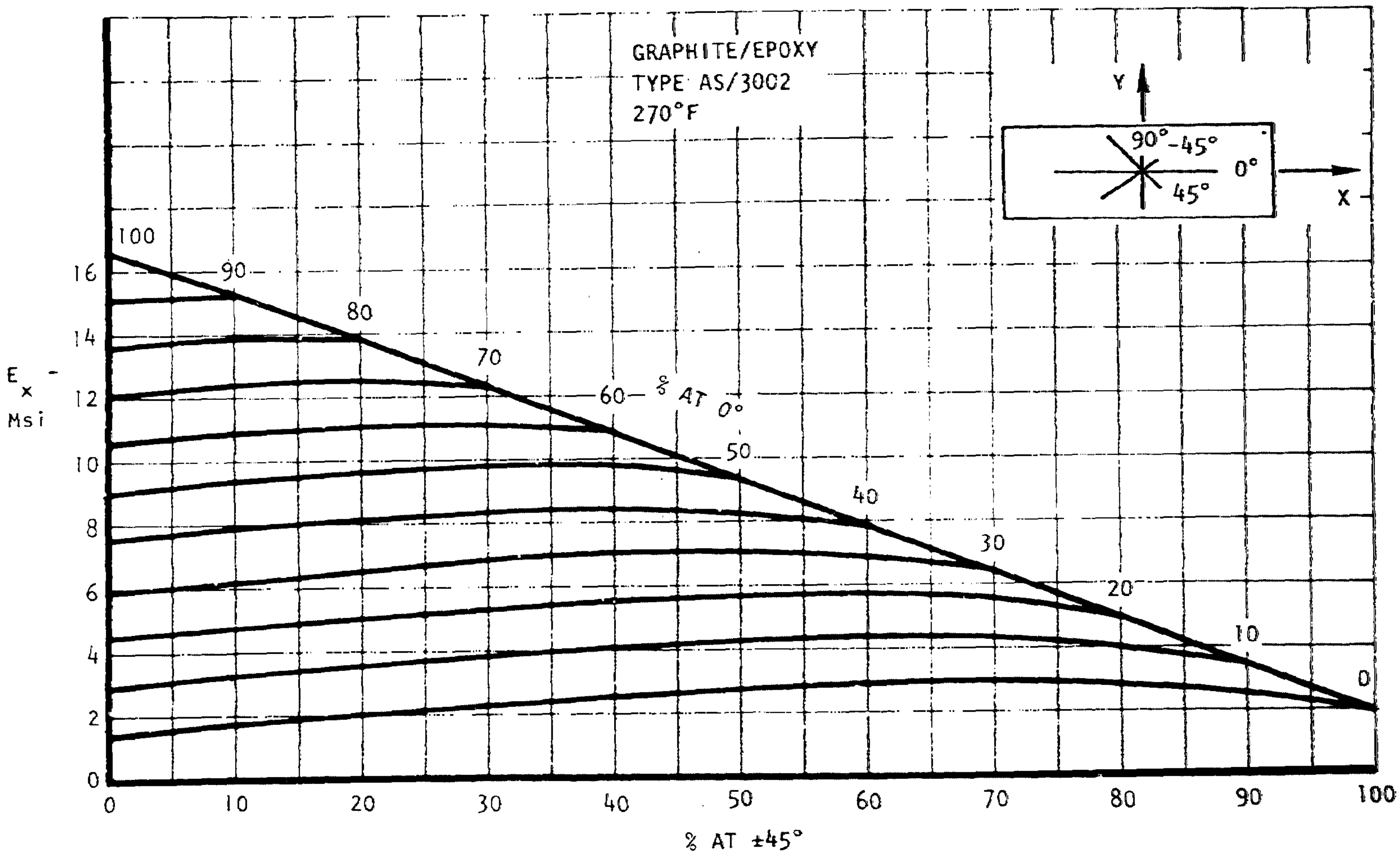


Figure 219. Laminate E_x Versus Percent Laminae, [0/±45/90] Family, for Graphite/Epoxy at 270°F

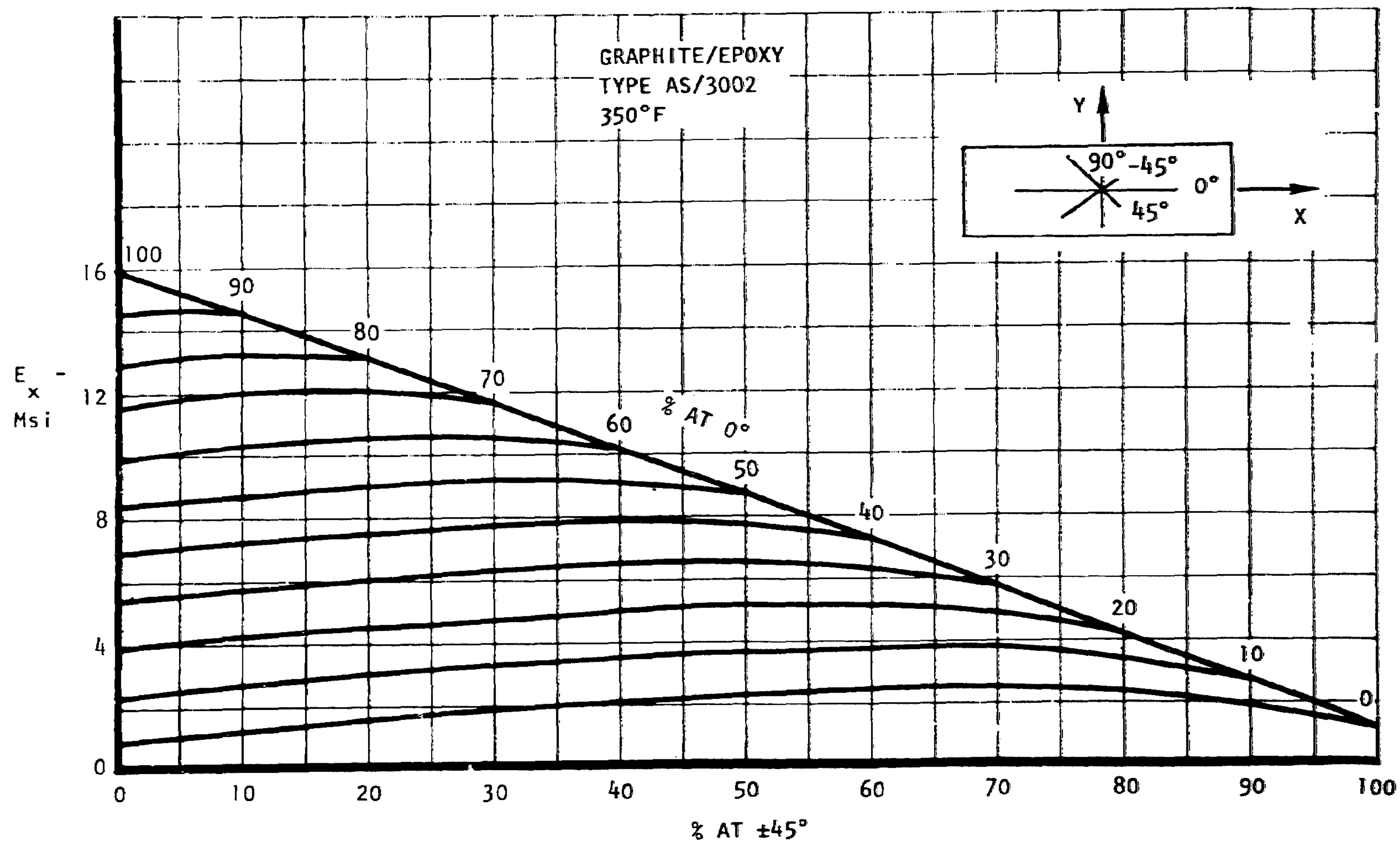


Figure 220. Laminate E_x Versus Percent of Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at 350°F

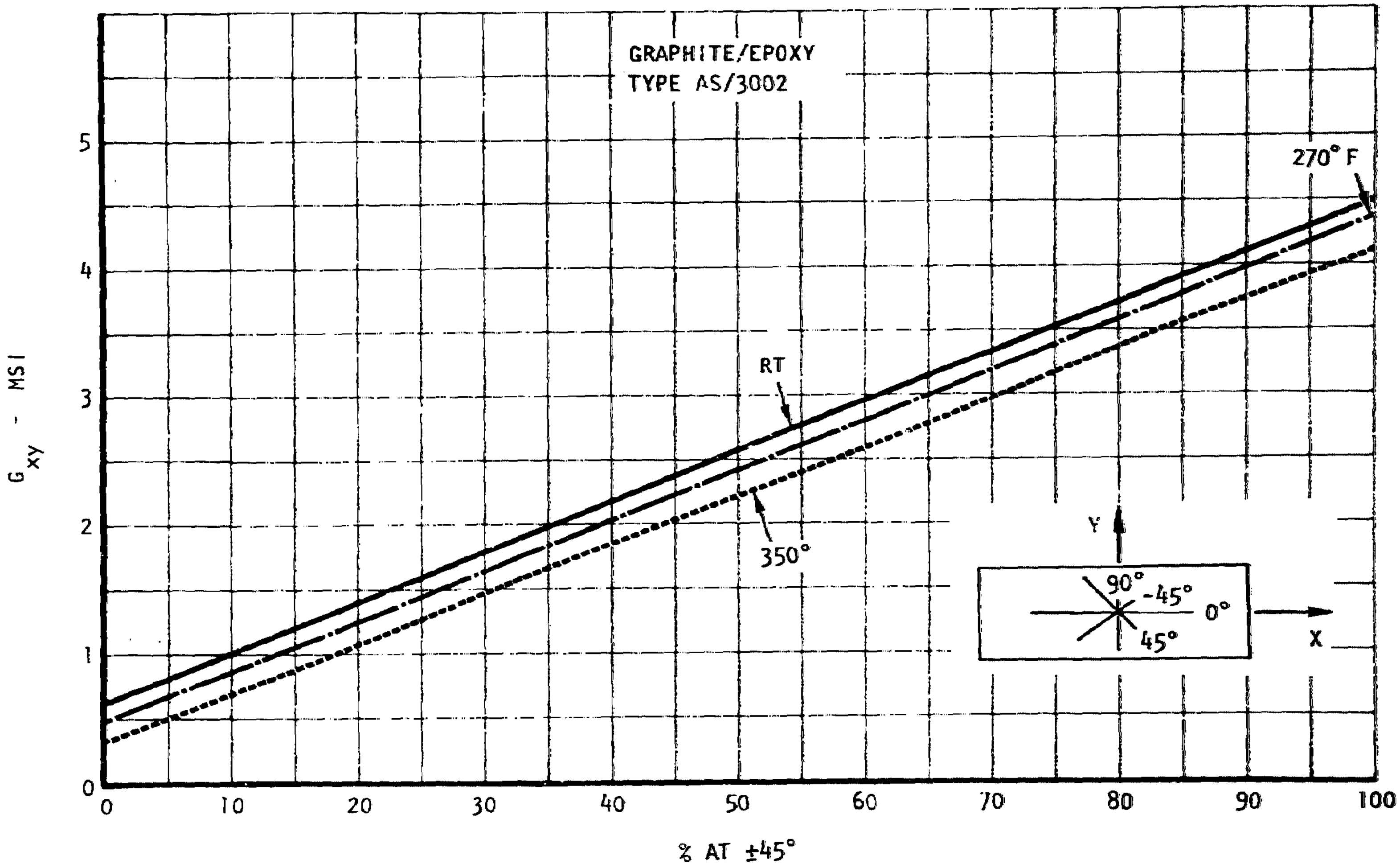


Figure 221. Laminate G_{xy} Versus Percent of Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at Room Temperature, 270°F, and 350° F

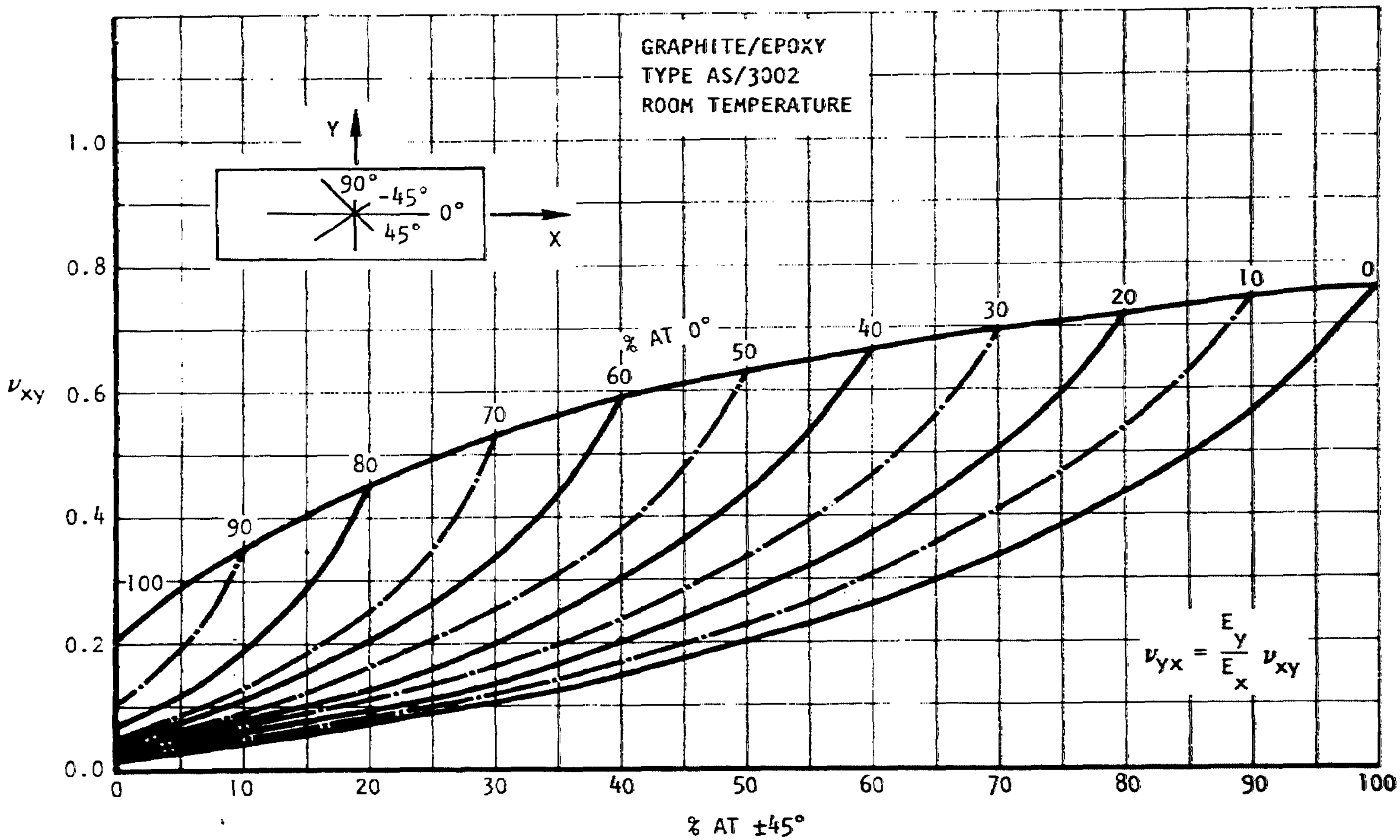


Figure 222. Laminate ν_{xy} Versus Percent of Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at Room Temperature

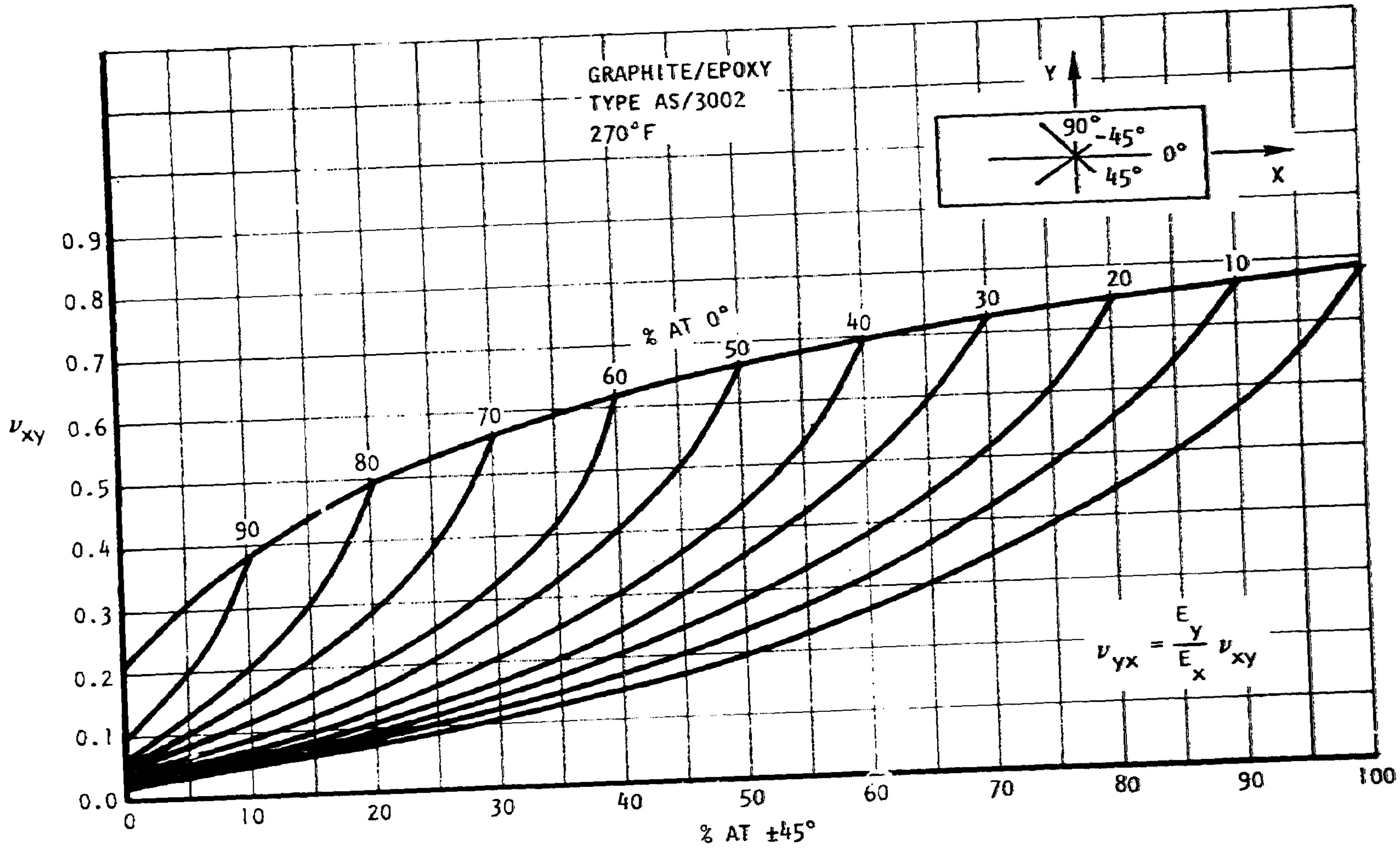


Figure 223. Laminate ν_{xy} Versus Percent Laminae, [0/±45/90] Family, for Graphite/Epoxy at 270°F

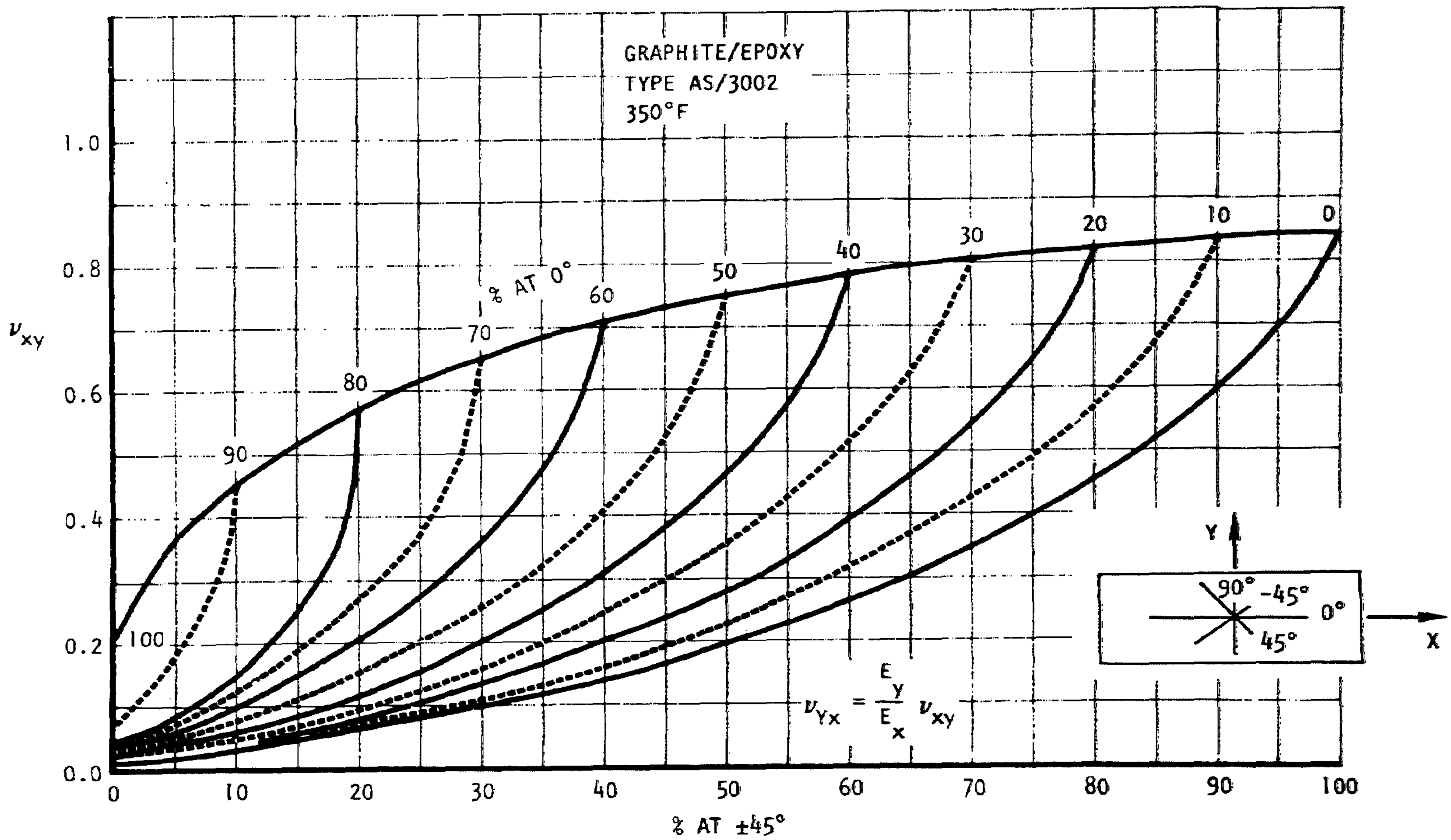


Figure 224. Laminate ν_{xy} Versus Percent of Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at 350° F

Coefficient of Thermal Expansion

Crossply coefficient of thermal expansion curves are presented in figures 225 and 226 for room temperature and 350°F, respectively. These curves are applicable to the $[0_i/\pm45_j/90_k]$ laminate family and were generated using an updated version of the AC 40 computer program described in reference 3 where a program logic routine was corrected. This modified version of AC 40 permits input of basic unidirectional graphite/epoxy properties to generate the crossply data. The room temperature curve (figure 225) supersedes the curve presented in reference 2.

SUMMARY OF SPECIFIC ORIENTATION - BASIC PROPERTIES

Table LXXXV presents a summary of basic strength and elastic properties at room temperature and 350°F for some representative laminate orientations of the $[0_i/\pm45_j/90_k]$ crossply family.

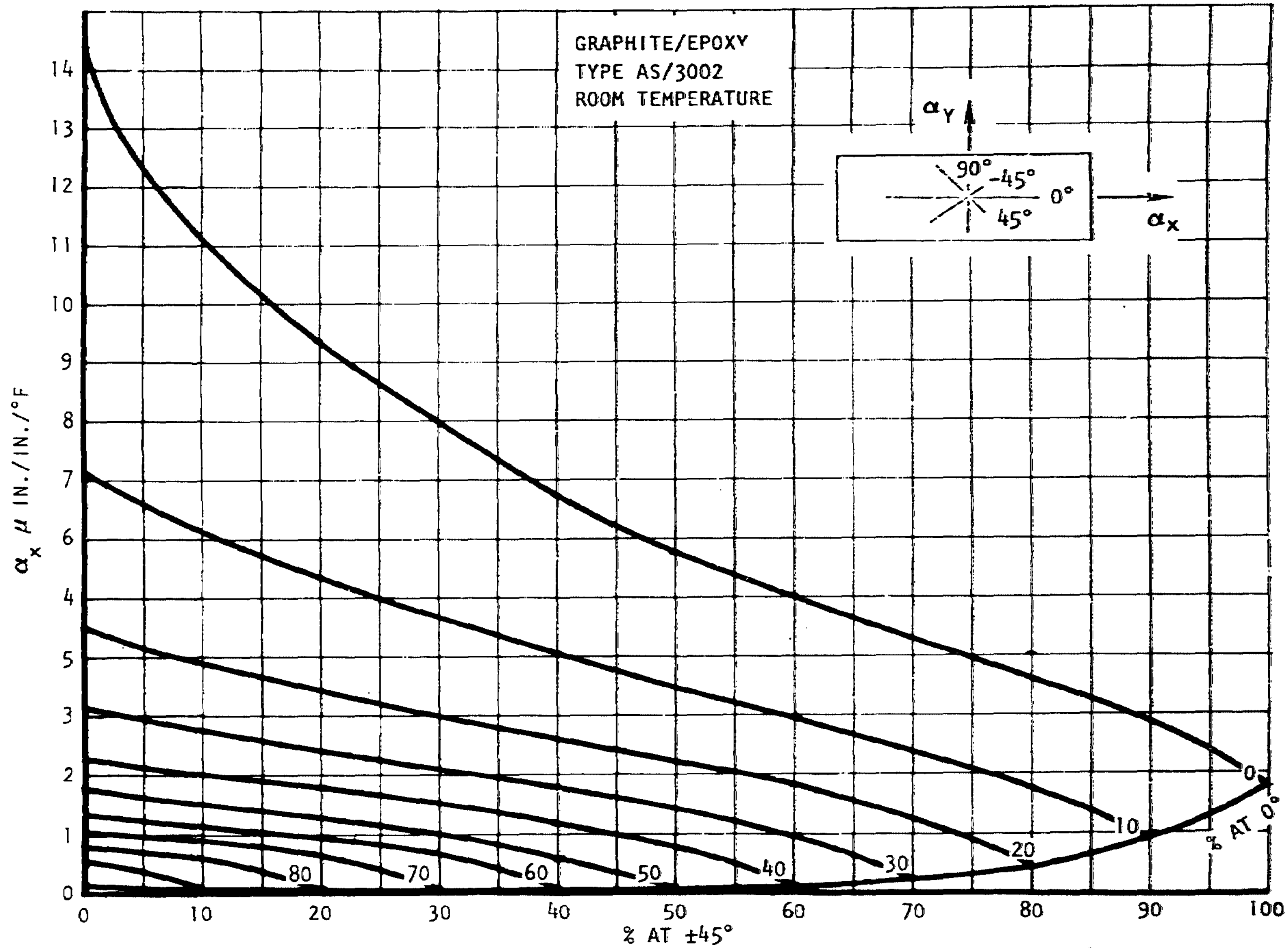


Figure 225. Laminate α_x Versus Percent of Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at Room Temperature

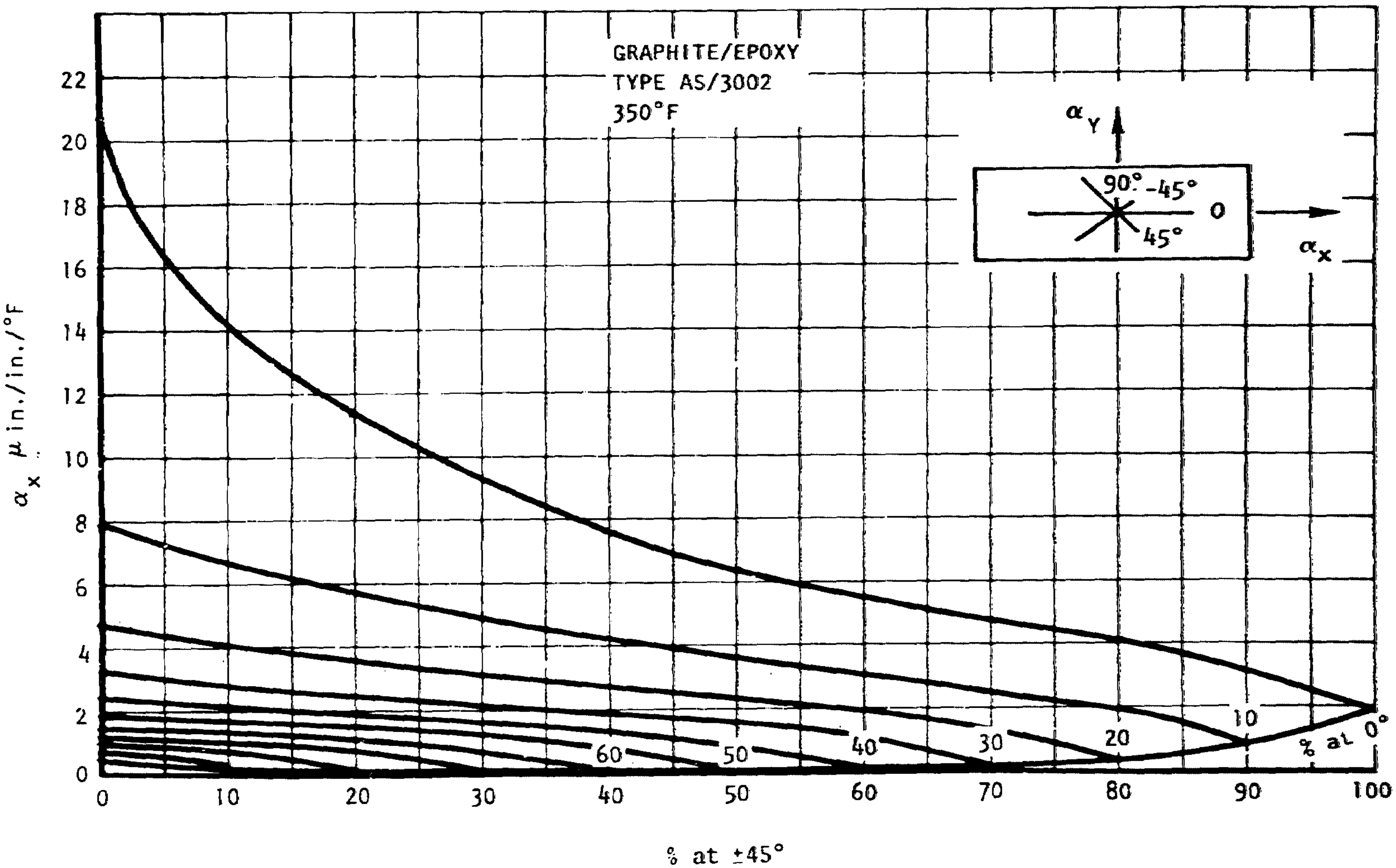


Figure 226. Laminate α_X Versus Percent of Laminae, [0/±45/90] Family, Graphite/Epoxy - Type AS/3002 at 350°F

TABLE LXXXV. DESIGN DATA SUMMARY - INTERMEDIATE STRENGTH FIBER (TYPE AS/3002)

Orientation	Temp (°F)	F_x^{tu} (Ksi)	F_x^{cu} (Ksi)	F_y^{tu} (Ksi)	F_y^{cu} (Ksi)	F_{xy}^{su} (Ksi)	E_x (Msi)	E_y (Msi)	G_{xy} (Msi)	ν_{xy} (in./in.)
[0]	RT	160	160	7.5	25	10	17	1.7	0.65	0.21
	350	144	65	4.0	15	4.0	16	1.0	0.36	0.21
[±45]	RT	23	23	23	23	50	2.4	2.4	4.5	0.76
	350	12	18	12	18	33.5	1.2	1.2	4.1	0.84
[0/±45]	RT	70	73	26	40	36	7.4	3.5	3.25	0.68
	350	57	35	20	22	23	6.3	2.6	2.85	0.80
[0/±45/90]	RT	64	66	64	66	28	6.7	6.7	2.6	0.31
	350	54	31	54	31	18	5.8	5.8	2.2	0.32
[0_2/±45]	RT	94	96	24	38	28	9.7	3.2	2.6	0.63
	350	80	42.5	19	19	18	8.8	2.3	2.2	0.75

CONFIGURATION INFLUENCE ON BASIC PROPERTIES

Table LXXXVI summarizes the effect of some basic configurations on basic laminate properties.

TABLE LXXXVI. CONFIGURATION INFLUENCE ON BASIC PROPERTIES

Configuration	Effect
Sandwich bending beam core density variation	Core variations from 3.1 to 5.7 pcf seemed to have little effect on either tension or compression strengths. These values were comparable to the standard (23 pcf core) bending beam strengths. (Refer to tables LIX to LXIII, and see figures 154 to 165.)
Single-stage versus secondary bonded bending beams	Tension strengths for single stage bonded beams were 25 percent lower than for secondary bonded beams. Likewise, compression strengths were 33 percent lower for the single stage bonded beams. (Refer to section IV, "Core Density Variation Sandwich Bending Beams.")
Open hole test	Tension loaded open holes exhibited net stress concentration factors ranging from 0.96 to 1.92 based on ultimate load. The data, therefore, show a reduction of the theoretical elastic stress concentration factor due to redistribution of stresses. (Refer to tables LXIV and LXV, and see figures 168 and 169.) The compression open hole data also showed stress concentrations comparable to tension data. The room temperature compression open hole net stresses were 6 to 51 percent lower than basic F^{cu}, while the 350°F values were 6 to 25 percent lower. (Refer to table LXVI and see figures 174 and 175.)
Thickness buildup tests	Thickness buildups of 1.5, 2, and 3 times the basic laminate thickness exhibited a 20 to 25 percent reduction in strength. Failures occurred away from the buildup area, hence indicating there was little induced stress concentration at the buildup. (Refer to table LXVII and see figure 181.)

FATIGUE PROPERTIES - BASIC LAMINATE

FATIGUE STRENGTH AT 10^6 CYCLES

Constant amplitude tension S-N data at room temperature are presented in figures 93 through 96, for unidirectional and crossply laminate orientations. Table LXXXVII summarizes this data in terms of the fatigue stress level at which cyclic life should exceed 10^6 cycles for an R factor of 0.05. The values are also expressed as percents of static "unnotched" or static "open hole" strengths.

PERCENT OF STATIC FATIGUE CURVES

Figure 227 presents lower bound constant amplitude fatigue curves for various laminate orientations for use as design guidelines. Both "unnotched" (K_t = 1) and "open hole" (K_t = 3) curves are shown for unidirectional $[0]_T$, and crossplied laminates of [0/±45], [90/±45], and [0/±45/90] orientations.

TABLE LXXXVII. CONSTANT AMPLITUDE TENSION FATIGUE STRENGTH AT 10^6 CYCLES FOR R = 0.05

Orientation	Configuration K_t*	Design Fatigue Strength at 10^6 Cycles: Cyclic Stress (Ksi)	Percent Static (%)
$[0]_{6T}$	1	95	60
	3	60	75
$[0/\pm45/90]_S$	1	34	53
	3	30	79
$[0/\pm45]_S$	1	44	63
	3	28	80
$[90/\pm45]_S$	1	16	50
	3	12	50

*K_t = 1 designates unnotched coupon
K_t = 3 designates coupon with a center hole

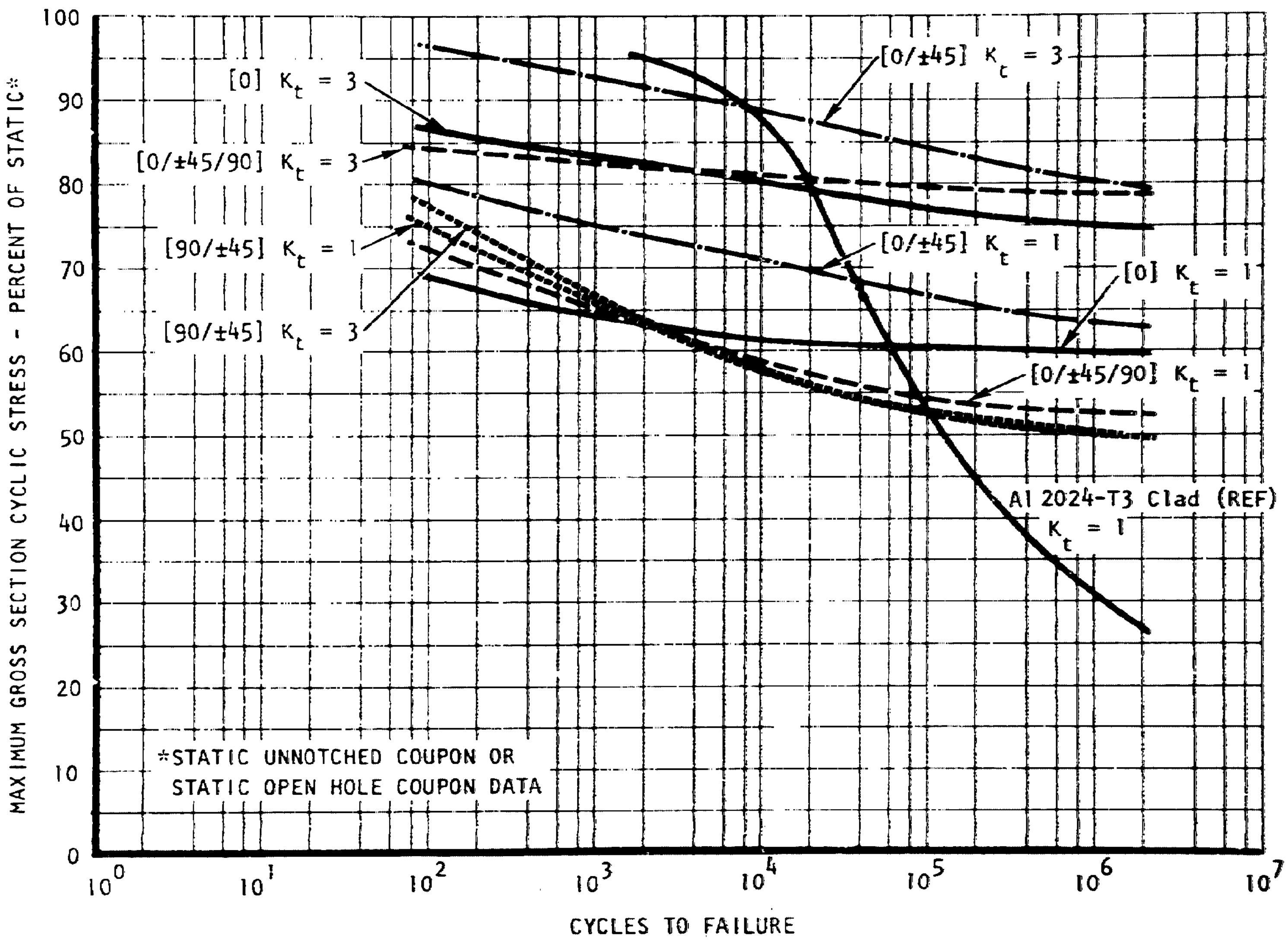


Figure 227. Constant Amplitude Fatigue, Graphite/Epoxy - Type AS/3002, $R = 0.05$, RT, $K_t = 1$ and 3

JOINT ALLOWABLES

BONDED JOINT STRENGTHS

Single Lap Joints

Static Allowables

Lower bound tension loaded single lap joint strengths are presented in figures 228 and 229 as N_x (lb/in.) versus lap length L_a, based on data presented in section IV. These curves show the expected leveling off of joint strength as lap length is increased. Figures 98, 101, and 104 present the test data in another form as bond shear stress, F_a^s versus L_a/t.

Lower bound compression loaded (sandwich stabilized) single lap joint strengths of figures 113, 114, and 115 show significant improvement over tension loaded single lap joints. Figure 230 presents lower bound compression loaded sandwich stabilized single lap joint strength, N_x versus L_a for the three laminate orientations designated.

Detailed single lap data are presented in tables XXXIII through XXXVII.

Fatigue Behavior

Tension lap joint constant amplitude fatigue data are shown in figures 123 and 124 for use as design guideline information. As a general rule, fatigue joint strengths for 10^6 cycles can be estimated at 40 to 50 percent of static joint strengths.

Symmetrical Double Scarf Joint

Static Allowables

Figures 231 and 232 summarizes the lower bound joint strength data of tension or compression loaded, symmetrical double scarf joints where the adherends are graphite/epoxy to titanium and the adhesive is Metlbond 329-7. Note that the sandwich stabilized, edgewise compression loaded scarf joint strengths are significantly greater than comparable joints loaded in tension. Detailed test data are presented in tables XXXVIII through XLI.

Fatigue Behavior

The tension fatigue behavior of symmetrical double scarf joints are presented in figures 127, 128, and 129 as S-N curves under an R factor of 0.05. These curves can be used for design guideline information. As a general rule, joint fatigue strengths for 10^6 cycles can be estimated at 35 to 50 percent of static joint strengths.

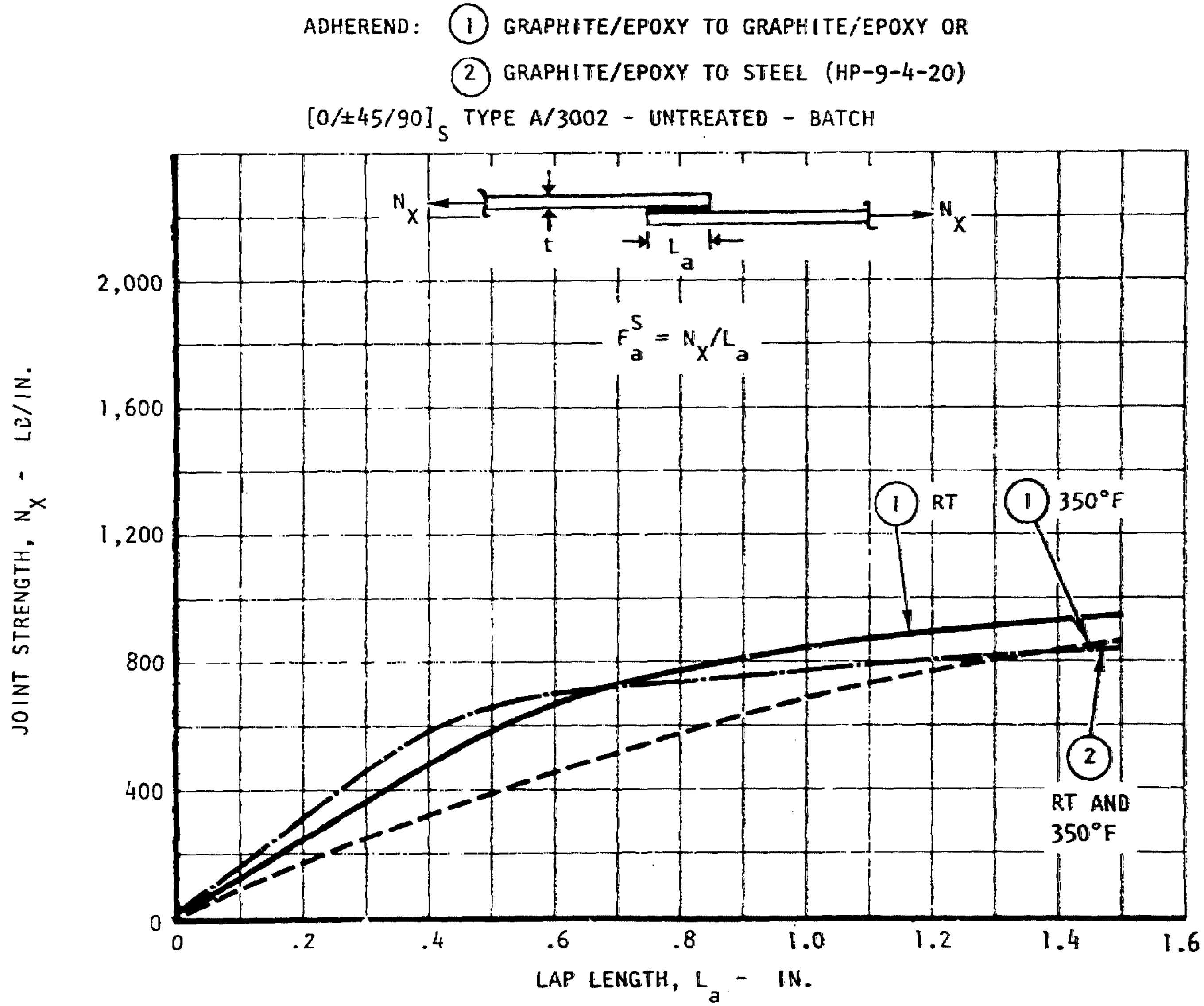


Figure 228. Lower Bound Tension Single Lap Joint Strength Versus Lap Length, - Type A/3002 - Graphite/Epoxy to Graphite/Epoxy or Steel, Metlbond 329-7 Adhesive

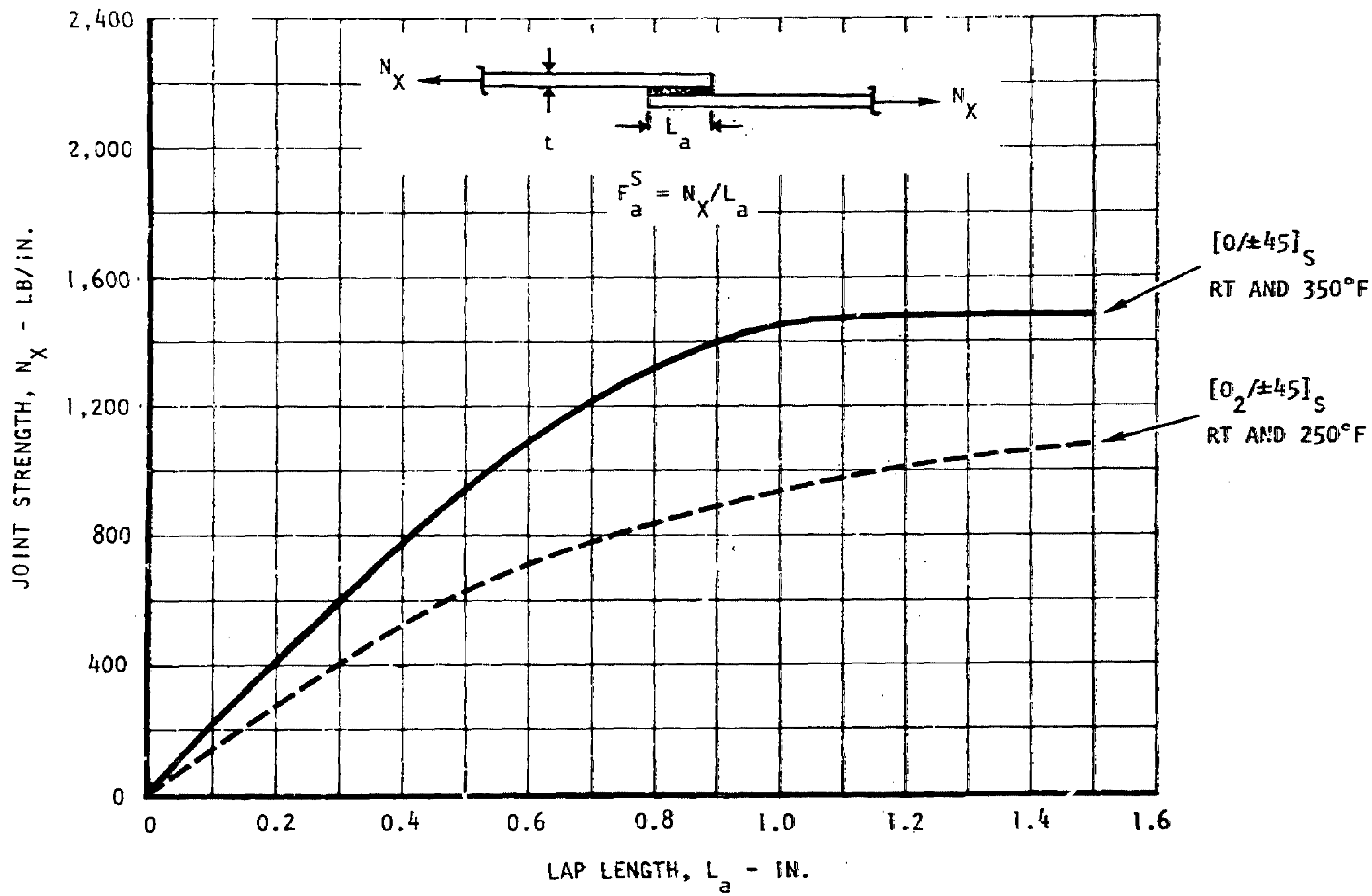


Figure 229. Lower Bound Tension Single Lap Joint Strength Versus Lap Length, - Type AS/3002 - Graphite/Epoxy Adherends, Metlbond 329-7 Adhesive

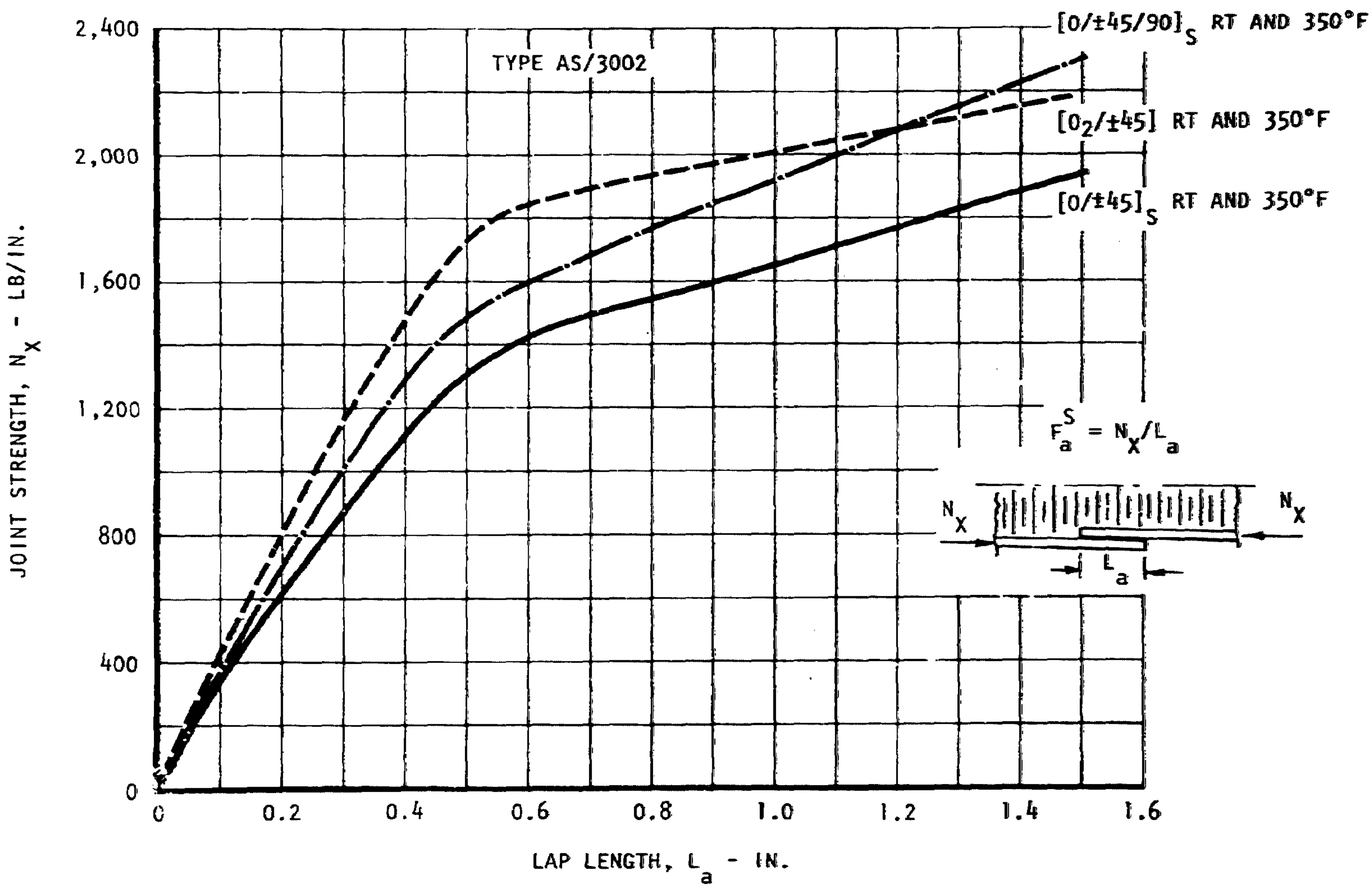


Figure 23?. Compression Loaded, Sandwich Stabilized, Lower Bound Single Lap Joint Strengths, Graphite/Epoxy Adherends, Metlbond 329-7 Adhesive

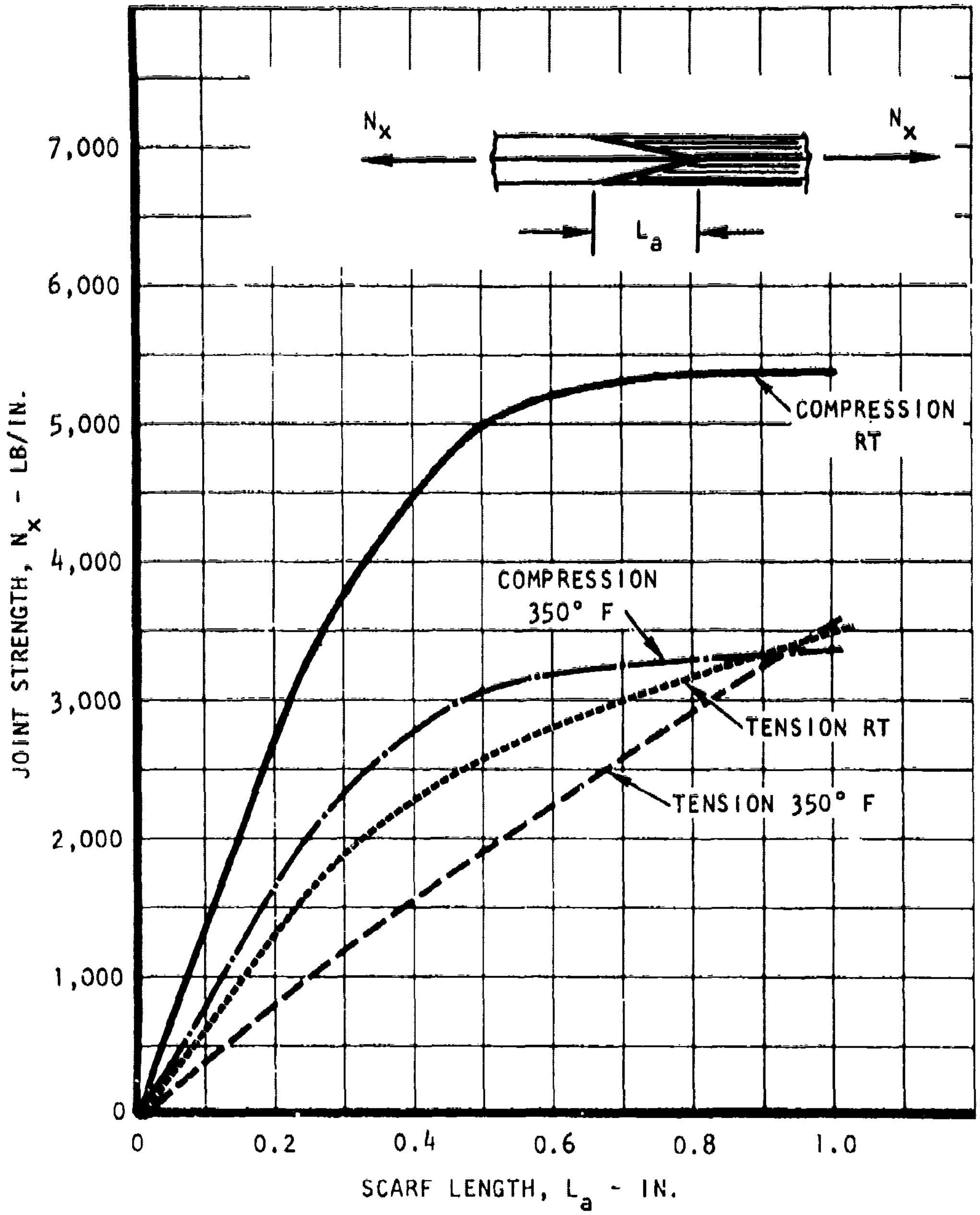


Figure 231. Symmetrical Double Scarf Lower Bound Joint Strength - Graphite/Epoxy to Titanium Adherends, Metlbond 329-7 Adhesive, Room Temperature and 350°F, $[0/\pm 45]_{2S}$

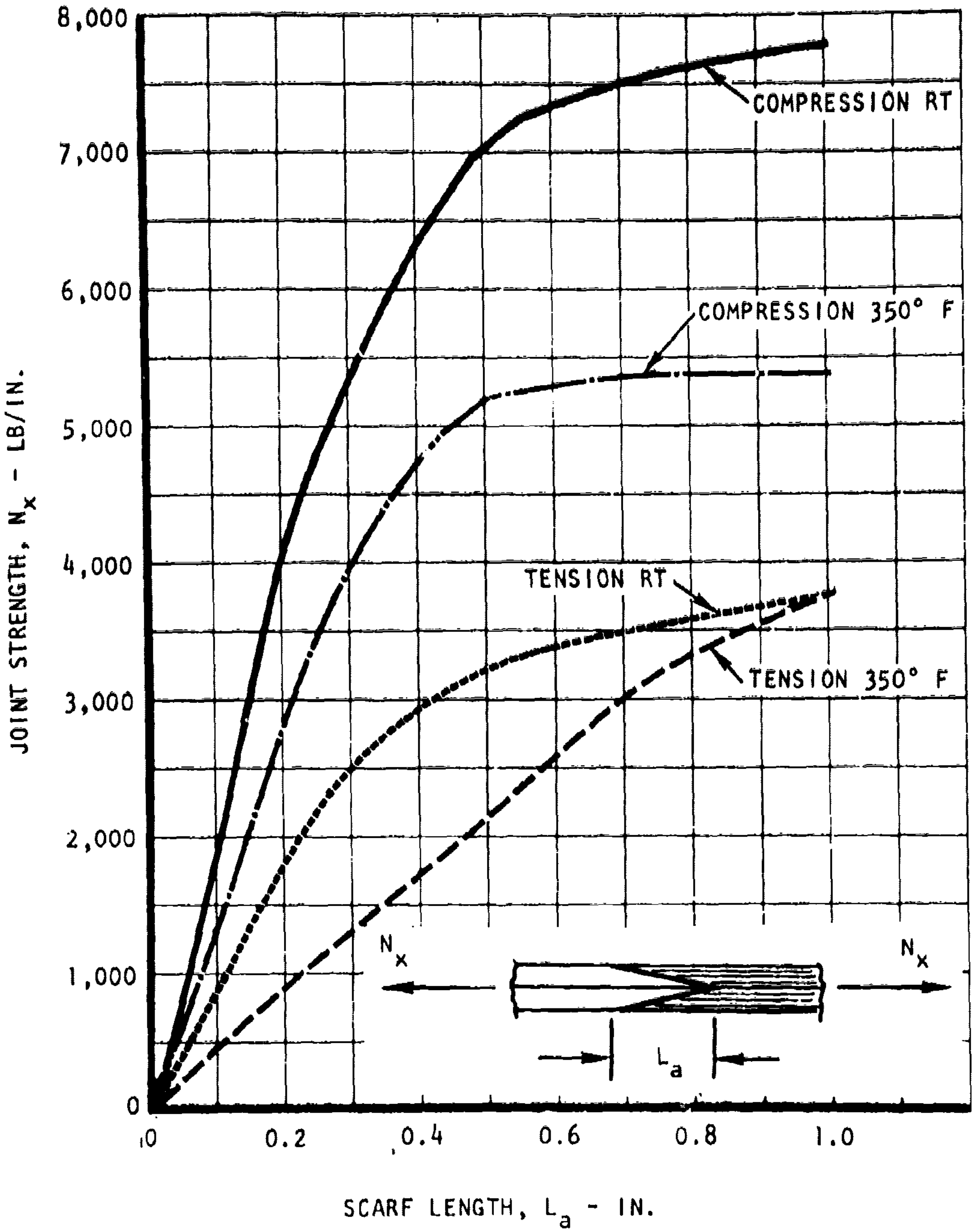


Figure 232. Symmetrical Double Scarf Lower Bound Joint Strength, Graphite/Epoxy to Titanium Adherends, Metlbond 329-7 Adhesive, Room Temperature and 350°F, $[0_2/\pm45]_{2S}$

MECHANICAL JOINT STRENGTHS

Flush Head Fastener Joint

Static Allowables

Figure 233 presents lower bound flush head fastener joint strengths in the form of equivalent bearing strength versus temperature for the graphite epoxy laminate orientations of $[0/\pm45/90]_{2S}$, $[0/\pm45]_{2S}$, and $[0_2/\pm45]_{2S}$.

Detailed data is presented in tables XLVIX, L, and LI, where data evaluation shows that the bearing strengths developed were independent of the e/D range (2.63 to 5.26) investigated. The limited compression loaded stabilized flush joints tested at room temperature averaged about 40% stronger than the tension loaded joints. (Refer to table LV.)

Fatigue Bahavior

The tension fatigue behavior of flush head fastened lap joints are presented in figure 152. The joint fatigue strength for 10^6 cycles can be estimated to be at least 60 percent of static joint strength for the three orientations investigated.

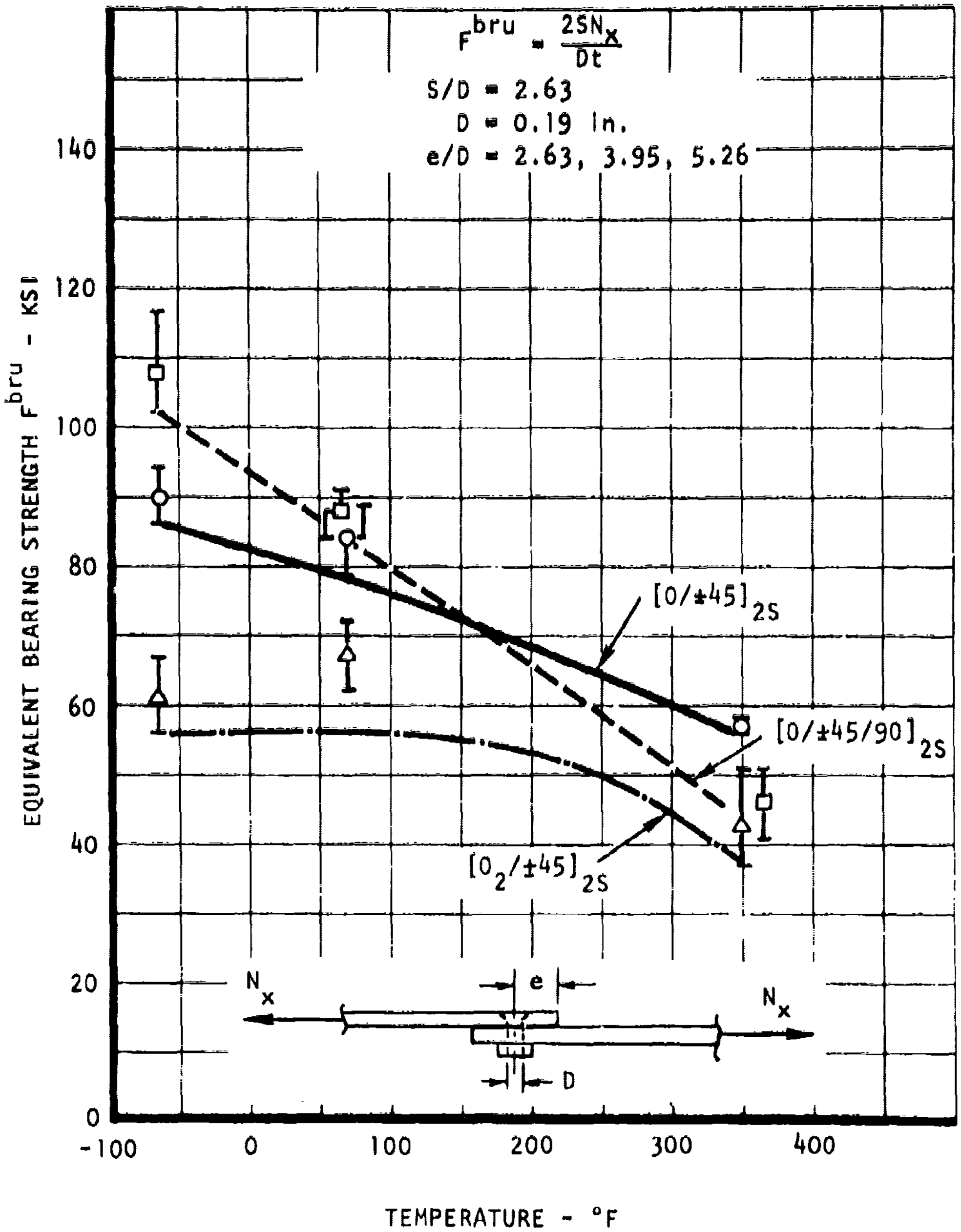


Figure 233. Mechanical Joint - Flush Fastener Lower Bound Bearing Strength Versus Temperature, Graphite/Epoxy

Protruding Head Fastener Joint

Static Allowables

Figure 234 presents lower bound protruding head joint strengths in the form of equivalent bearing strength versus temperature for graphite/epoxy laminate orientations of $[0/\pm45/90]_S$, $[0/\pm45]_S$, and $[0_2/\pm45]_S$. Data evaluation in section IV shows that the bearing strengths were generally independent of the e/D range (2.63 to 5.26) investigated. Detailed data are given in tables LII, LIII, and LIV. The limited compression loaded stabilized protruding head fastener joints tested at room temperature averaged about 13% lower strengths than the tension loaded joints. (Refer to table LVI.)

Fatigue Behavior

Tension joint fatigue behavior of protruding head lap joints are presented in figure 153. The joint fatigue strength for 10^6 cycles can be estimated to be 70 percent of static joint strengths.

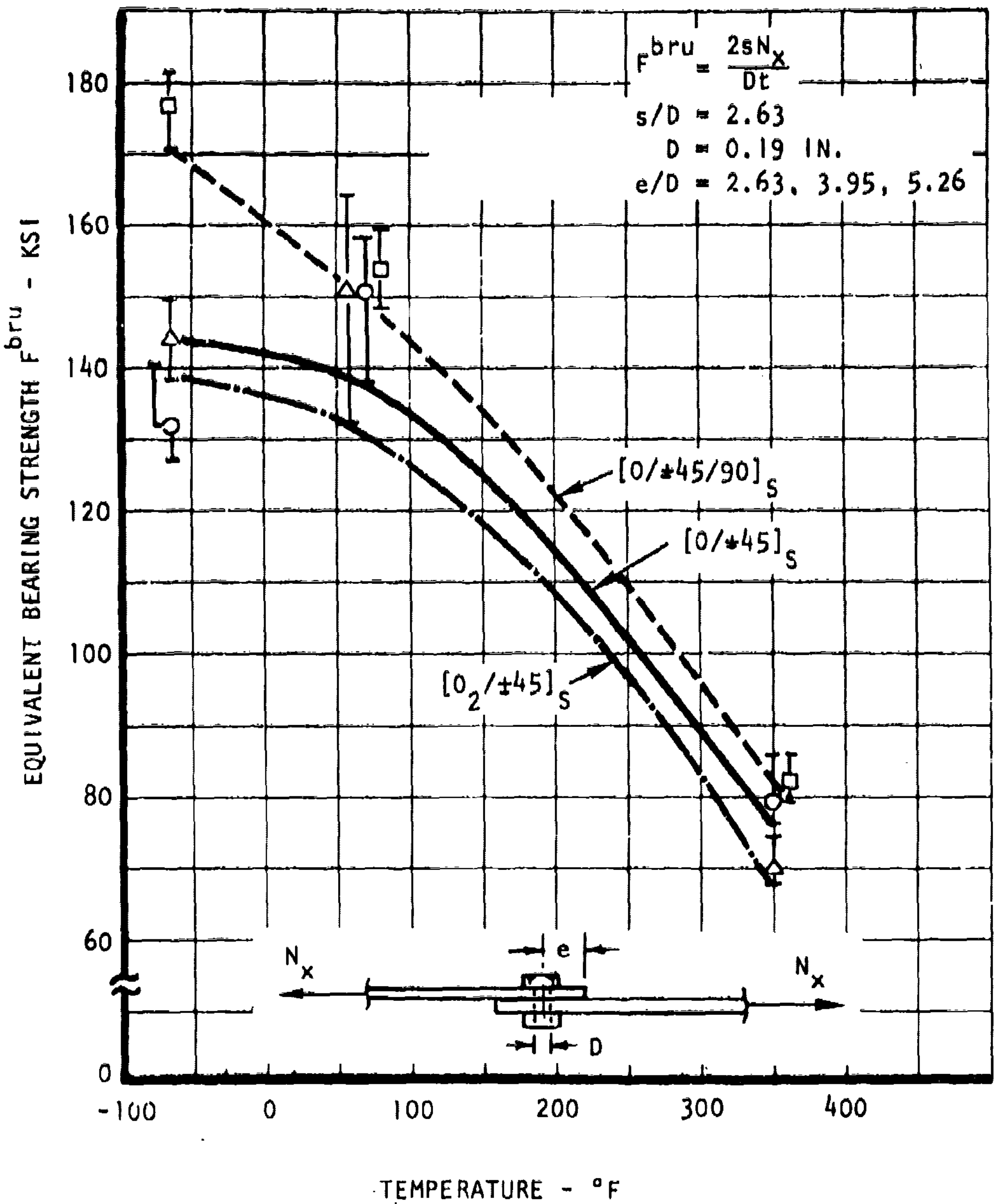


Figure 234. Mechanical Joint - Protruding Head Fastener Lower Bound Bearing Strength Versus Temperature, Graphite/Epoxy

ENVIRONMENTAL EFFECTS

Table LXXXVIII summaries the effects of various environments on Type AS/3002 batch graphite/epoxy laminate mechanical properties.

TABLE LXXXVIII. ENVIRONMENTAL EFFECTS SUMMARY

Environment	Effect
Thermal cycling 10, 100, 500 cycles 1 cycle = R T to 270°F to R T	RT and 270°F longitudinal flexure strengths were unaffected. Transverse flexure strengths at RT and 270°F were unaffected at 10 and 100 cycles. At 500 cycles, there was a 22% decrease in RT transverse flexure strength and a 7% decrease in 270°F transverse flexure strength. The RT and 270°F interlaminar shear strengths were within 15% of the control values for 10 to 500 cycles. (See figures 182 and 183, and refer to table LXVIII.) Bonded joint strengths were reduced by an average of 19 percent due to thermal cycling. (See figure 185 and refer to table LXIX.) Mechanical joint strengths were unaffected. (See figure 187 and refer to table LXX.)
Radiation exposure (refer to table LXXI)	No degradation in longitudinal, transverse flexure, or horizontal shear strengths. (Refer to table LXXII.)
Thermal pulse (simulated nuclear blast with 15 Ksi preload)	20 percent degradation in tension and compression strengths. Stiffness was unaffected. (Refer to tables LXXIII and LXXIV and see figures 196 and 197.)
98% relative humidity 120°F for 35 days	RT longitudinal flexure strength was unaffected. The 270°F and 350°F longitudinal flexure strengths were 60 and 70% lower than controls. RT, 270°F, and

Table LXXXVIII (Continued)

Environment	Effect
	350°F transverse flexure and interlaminar shear strengths were reduced by 10 to 75%. (See figures 198 through 200, and refer to table LXXV.)
Salt spray - 5% salt solution 95°F for 35 days	RT longitudinal flexure strength was unaffected, while the 270°F and 350°F longitudinal flexure strengths were reduced by 13 and 53%, respectively. RT and 270°F transverse flexure strengths were decreased by 36%, and 350°F transverse flexure strength was unaffected. RT, 270°F, and 350°F interlaminar shear strengths were reduced by 14, 33, and 40%, respectively. (See figures 198 through 200 and refer to table LXXV.)
Weathering – panel placed on rooftop for 35 days	RT and 270°F longitudinal flexure and interlaminar shear strengths were unaffected by weathering of both coated and uncoated panels. (See figures 198, 200 and refer to table LXXV.)
Fluids – permeability (JP-4 fuel)	No fuel penetration through laminates. Fuel absorbed caused average weight gains of 0.06 and 0.11% for unsanded and sanded surface specimens. (2.5 sq in. surface areas) (Refer to table LXXVI.)
Thermal aging 500 hours at 270°F	RT and 270°F longitudinal flexure and interlaminar shear strengths were unaffected by 500 hours thermal aging at 270°F. The room temperature and 270°F transverse flexure strengths were both reduced to about 82% of the control values. (See figures 202 through 204 and refer to table LXXVII.)

Table LXXXVIII (Concluded)

Environment	Effect
Thermal aging 500 hours at 350°F	Longitudinal flexure strength was unaffected for both RT and 350°F. Transverse flexure strength at RT was 10% lower than control, while the 350°F transverse flexure strength was 269% higher than the control value. The RT interlaminar shear strength was decreased by 12%, while the 350°F strength was unaffected.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

This program provided the generation and presentation of basic engineering data necessary to perform high-confidence-level structural design of aircraft structures utilizing advanced composite materials. Specifically, this volume provided the baseline data of basic material properties, bonded and mechanical joint data, and configuration data for the singular graphite/epoxy system known as Type AS/3002. In addition, the environmental effects portion of the test program established the influence of the operating environment on the design allowables.

The following significant conclusions and recommendations can be made:

1. The crossplied calculated design properties (strengths, elastic, and physical constants) generated on this program using unidirectional baseline input data generally exhibited very good correlation with the baseline test data and yielded conservative or comparable values with tests conducted on this program and with data within the industry.

2. The analytic techniques used to generate material allowables are still dependent on empirical modifications such as that used for compression properties where a high percentage of ±45 plies occur.

3. Material property extrapolations to other laminate orientations not tested in this program can be made with a high degree of confidence for preliminary design purposes.

4. Crossplied laminates with [±45] or [90] ply midsurface plies exhibited significantly lower interlaminar shear stresses than the conventional unidirectional [0] based on short beam tests. In all cases, however, the interlaminar shear strengths were greater than the bonded lap joint shear strengths.

5. Joint allowables of bonded lap or double scarf configurations using Metlbond 329-7 adhesive have been generated.

6. Flush and protruding head mechanically fastened single lap joint allowables have been generated for the specific laminate orientations and geometries required to insure bearing type failures. Extension to other laminate orientations can be made, but further "spot testing" for other orientations are desirable.

7. Strength degradations of approximately 25 percent in tension and 33 percent in compression for "cocured" or "single stage" bonded sandwich structure were established.

8. Environmental effects tests have verified that moisture or humidity environment has a detrimental influence on quality control data at elevated temperature (350°F).

9. Torsional tube type tests are recommended to verify the computed unidirectional shear stress-strain data which was indirectly calculated from ±45 tension coupon data.

10. Additional crossply laminate orientations are recommended for the mechanical joint configurations to establish "end point" values for carpet plot type data presentation.

APPENDIX I

NR/LAD SPECIFICATION ST0130LB0005

ADVANCED COMPOSITE MATERIAL -

GRAPHITE/EPOXY PREPREG

HIGH MODULUS, HIGH STRENGTH

PREPARED BY	CODE IDENT. NO. 43999	NUMBER STO130LB0005
T. W. McGann	NORTH AMERICAN ROCKWELL CORPORATION AEROSPACE AND SYSTEMS OPERATIONS	TYPE Material
APPROVALS		DATE 6/5/71
	SPECIFICATION	SUPERSEDES SPEC. DATED: 5/12/71
		REV. LTR. B — PAGE 1 of 20

TITLE

ADVANCED COMPOSITE MATERIAL - GRAPHITE EPOXY PREPREG, HIGH MODULUS, HIGH STRENGTH

TABLE OF CONTENTS

1. SCOPE

1.1 This specification establishes the requirements for high strength, high modulus, thermosetting resin treated, parallel in-plane collimated, multifilament graphite tow preimpregnated material.

1.2 Classification

1.2.1 Resin Type. - The impregnating resin shall be classified as follows:

Type	Description of Impregnating Resin
I	General Purpose (200° F max; continuous exposure up to 10,000 hours)
II	Heat Resistant (350° F max; continuous exposure up to 1,000 hours)
III (Future)	High Heat Resistant (500° F max; continuous exposure up to 1,000 hours)

1.2.2 Impregnated Graphite Tow.

Class	
1	High modulus, nominal fiber modulus 50×10^6 psi
2	High strength, ultimate fiber tensile strength 350 ksi, minimum
3	Intermediate strength, ultimate fiber tensile strength 250 ksi, minimum.

Grade	
1	Meter lengths - batch process
2	Continuous length - continuous process

2. APPLICABLE DOCUMENTS

2.1 Documents. The latest issues of the following documents form a part of this specification to the extent specified herein:

SPECIFICATIONS

STANDARDS

Federal

Federal Test Method Std No. 406	Plastics: Method of Testing

Military

MIL-STD-414	Sampling Procedures and Tables for Inspection by Variables for Percent Defective

3. REQUIREMENTS

3.1 General. Preimpregnated materials covered by this specification shall consist of parallel in-plane, collimated graphite fiber or tow, high modulus, or high strength, and impregnated with the applicable thermo-setting resin as specified. They shall be capable of being molded, using low pressure laminating methods (under 100 psi), to produce a cured molding having properties described in this specification.

3.2 Materials Procured by the Supplier.

3.2.1 Impregnating Resin. The resin used for types I and II shall conform to the general requirements of the prepreg supplier. The resin shall be free of foreign materials, noncorrosive to metals and shall be capable of being molded, using low pressure laminating methods, to a fully thermoset state and meet the requirements of this specification.

3.2.2 Graphite Tow.

a. Material - The graphite fiber or tow supplied to the processor shall meet the requirements of the prepreg supplier.

3.3 Material Procured by North American Rockwell Corporation

(NR) - Graphite tow uncured plastic preimpregnated material, class 1, class 2, and class 3, shall consist of collimated, parallel in plane graphite tows impregnated with thermosetting resin (see 3.2.1) and shall be supplied by the linear foot of tape of a specified width or in broadgoods form of a specified length and width by the procuring activity.

a. The physical properties of the uncured prepreg material shall be in accordance with the requirements shown in Table II.

3.3.1 Graphite Tow Count. Preimpregnated material shall contain 5 ±.1 tow ends per inch of width for both grade 1 and grade 2 material.

3.3.2 Graphite Tow Gaps. Spacing between adjacent tows shall be .020 inch maximum with length of such a gap 4.0 inches maximum. No more than two such gaps per three inches in width and twelve inches in length, on any one sheet or roll, shall be acceptable.

3.3.3 Graphite Tow Splices. Splices on adjacent yarns or tows for grade 2 material situated within one-half inch of each other shall not be acceptable. Splices in grade 1 material shall be cause for rejection.

3.3.4 Graphite Tow Alignment. All tows shall be collimated and parallel to the centerline of the prepreg meeting the following alignment requirements; the lay of the yarn or tow within the tape or sheet shall not deviate from a straight line by more than 1/32 inch in one foot of length. The edge of the sheet or tape shall not deviate from a straight line by more than 1/16 inch per foot of length for sheet and .010 inch per foot of length for tape.

3.3.5 Prepreg Width. Prepreg material shall be furnished in specified tape widths or in broadgoods form of specified width.

Table II

UNCURED PREPREG, PHYSICAL PROPERTIES

Property	Requirement
Volatile content, percent by weight	8% maximum
Resin solids, percent by weight	42 $\pm$4
Tack	Shall adhere to itself when wrapped on a 2.0 inch mandrel, yet release from the carrier paper in a manner to permit continuous tape laying. (Note 6.2)
Gel Time at 177° C (350° F), minutes	7-11
Drapability	Shall bend on a 1/16 inch radius mandrel with no evidence of tow damage. (Note 6.2)

3.3.6 Prepreg Length. Prepreg material shall be furnished either in a roll of specified length for tape or of specified length in the broadgoods form.

3.3.7 Prepreg Uniformity. Each roll or sheet of prepreg material shall be of uniform quality throughout. Defects such as resin rich or starved spots, tow overlay, or discontinuity shall be maintained at a consistently minimum level.

3.3.8 Storage Life (Shelf Life). The prepreg material shall meet the requirements of this specification after storage of 3 months at temperatures not exceeding 0° F or a minimum of 10 days storage at 75° F maximum.

3.3.9 Workmanship. Prepreg material furnished to this specification shall be of quality workmanship and shall be free of all impurities and defects which could adversely affect its performance. Visible indication of dry spots, voids, crossed, crimped, or broken tows, or incomplete impregnation shall be marked by inserts and shall be cause for rejection only if the total length of such areas exceeds 6 percent of the total tape or sheet area.

3.4 Cured Prepreg. Mechanical properties of cured laminated prepreg shall conform to requirements listed in Table III when fabricated and tested in accordance with 4.23.

3.5 Identification Marking. (See 5.2.1)

Table III

REQUIREMENTS FOR MECHANICAL PROPERTIES OF CURED LAMINATES (NOTE 1 & 2)

Property	Temperature °F	Ultimate Value, Type I and Type II					
		Class 1		Class 2		Class 3	
		Grade 1	Grade 2	Grade 1	Grade 2	Grade 1	Grade 2
Flexural Strength, min., ksi	R.T.	140	140	200	200	200	200
	350 (Type II only)	105	105	150	150	150	150
Tensile Strength, min., ksi	R.T.	130	130	180	180	160	160
Tensile Modulus, min., avg., MSI	R.T.	27	27	21	21	17	17
Interlaminar Shear Strength, min., avg., ksi	R.T.	9.0	9.0	13.0	13.0	13.0	13.0
	350 (Type II only)	5.0	5.0	8.0	8.0	8.0	8.0

NOTES:

1. These requirements have been normalized to a fiber volume of 60%

2. All combinations of types, classes, and grades of graphite prepreg are required to mold to a cured thickness of .0060 ± .0004 inches/ply.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection. The supplier shall be responsible for the performance of all inspection requirements specified herein. The supplier may utilize his own facilities or any commercial laboratory acceptable to NR. NR reserves the right to perform or witness any of the inspections specified herein, when these inspections are deemed necessary to substantiate prescribed requirements.

4.2 Certificate of Conformance. The supplier shall furnish with each shipment a certified report (in triplicate), stating conformance to the requirements specified herein and listing the specific results of all the quality conformance inspection tests. This report shall also include this specification number, type and class, fiber density (to 4 decimal places), fiber tensile strength, fiber tensile modulus (per lot supplied to the pre-pregger), the purchase order number, the batch number, roll number or sheet number and footage in each, manufacturer's designation and date of manufacture. An itemized description of any rejected material including linear footage of such rejects and their location shall also be included.

4.3 Subcontractor. When materials for subcontract fabrication are purchased directly by the subcontractor, the subcontractor shall be responsible for determining that the material meets all the requirements of this specification. With each part shipment the subcontractor shall submit a copy of the report specified in 4.2.

4.4 Inspection Records. The supplier's inspection records of examination and tests for conformance to the requirements of this specification shall be kept complete and available to NR upon request.

4.5 Inspection Lot. A lot shall consist of all the material forming part of one purchase order and submitted for acceptance at one time. A batch shall be that quantity of material compounded and manufactured at one time.

4.5.1 Level of Inspection. Each batch in each lot shall be tested for conformance to the quality conformance inspection requirements.

4.6 Classification of Inspections. The inspections requirements specified herein are classified as follows:

1. Qualification Inspection (See 4.7)

2. Quality Conformance Inspection (See 4.8)

Table IV

QUALIFICATION INSPECTION

Test	Requirement Paragraph	Method Paragraph
Impregnating Resin		
Conformance	3.2.1	4.11
Graphite Tow Properties		
Conformance	3.2.2	4.12
Uncured Prepreg		
Volatile content	3.3a	4.13
Resin content	3.3a	4.14
Tack	3.3a	4.15
Gel time	3.3a	4.16
Drapability	3.3a	4.17
Graphite tow count	3.3.1	4.18
Graphite tow gaps	3.3.2	4.18
Graphite tow splices	3.3.3	4.18
Graphite tow alignment	3.3.4	4.18
Prepreg width	3.3.5	4.19
Prepreg length	3.3.6	4.19
Prepreg uniformity	3.3.7	4.20
Storage life	3.3.8	4.21
Workmanship	3.3.9	4.22
Cured Prepreg		
Cured thickness/ply	3.4	4.23.1
Flexural strength (ult) and flexual modulus, longitudinal	3.4	4.23.2
Tensile strength (ult) and tensile modulus	3.4	4.23.3
Interlaminar shear strength	3.4	4.23.4
Fiber volume	3.4	4.23.5

4.7 Qualification Tests. Qualification inspection tests shall be as specified in table IV.

4.7.1 Requalifications. Any change in formulation shall be submitted by the manufacturer in writing to the NR Engineering Materials & Producibility via the Purchasing Department. The material shall then be subject to requalification.

4.8 Quality Conformance Tests. Quality conformance inspection tests shall consist of all tests listed for the uncured prepreg (see 3.3) and the longitudinal flexure, interlaminar shear (3 specimens each at R. T. and 350°F), and fiber volume tests for the cured prepreg as listed in Table III. Tensile strength and modulus determination shall be required only for the initial qualification of a system.

4.9 Test Conditions.

4.9.1 Standard Conditions. Unless otherwise specified herein, all room temperature tests shall be conducted at a temperature of 75° to 79° F, and a relative humidity of 45 to 55 percent.

4.10 Test Specimen Preparation. Test panels from which test specimens will be prepared shall be fabricated in accordance with 4.23. Test specimens shall be cut from the test panel prepared, using diamond studded cutters.

4.11 Conformance of the Resin. The impregnating resin shall be tested for conformance to the applicable requirements of the prepreg supplier.

4.12 Graphite Tow Properties. The acceptability of graphite tow properties shall be determined by the supplier in a manner commensurate with his facilities.

4.13 Volatile Content. A 3 x 3 inch square of 1 ply uncured prepreg shall be weighed to the nearest 0.001 gram (W_1) and heated in an air circulating oven for 20 ± 0.5 minutes at 320° to 330° F. The specimen is then removed, cooled in a desiccator to ambient conditions and reweighed to the nearest 0.001 gram (W_2). The volatile content in percent shall be 100 $(W_1-W_2)/W_1$. The mean percent volatile content shall be based on the average of three specimens. (NOTE 6.3)

4.14 Resin Content. A sample of prepreg weighing between one and three grams shall be weighed to the nearest 0.001 gram (W_1) and placed in a solution of boiling MEK (methyl ethyl ketone) or DMF (dimethyl formalide) for five minutes or until all resin appears to be completely dissolved. The fibers shall then be washed twice with acetone. Dry the graphite fibers in an air circulating oven maintained at 325° F for one hour; remove the fibers and cool to ambient conditions in a desiccator. Remove the fibers and weigh to the nearest 0.001 gram (W_2). The resin content in percent shall be 100 $(W_1-W_2)/W_1$. The mean percent resin content shall be based on the average of three specimens.

4.15 Tack. The tack shall be determined by wrapping a 3 x 10 inch piece of prepreg around a 2 inch diameter mandrel so that each layer will be in contact with the next.

4.16 Gel Time. The gel time shall be determined on a specimen consisting of 4 one-inch squares of prepreg, with alternating plies of 90° to each other. The specimen shall be placed in a platen press preheated to 350° F ±5. The press shall be closed just sufficient to form beads of extruded resin. The beads shall be probed with suitable rods until long strings or threads of resin cease to form. Gel time is the length of time between initial forming of the beads and the moment the long strings or threads of resin cease to form. (NOTE 6.3)

4.17 Drapability. The drapability shall be determined by bending a 2 inch long by 3 inch wide specimen of prepreg over a 1/16 inch radius mandrel. This test shall be repeated three times. (NOTE 6.2)

4.18 Graphite Tow Count, Tow Gaps, Tow Splices, and Tow Alignment. The uncured prepreg shall be examined visually, using magnification if necessary, to make the count of graphite tows, to measure the gaps, and to check for splices. The alignment shall be checked using a square and a scale or other suitable instrument.

4.19 Prepreg Width and Length. The width and length of the prepreg shall conform to the requirements of the purchase order.

4.20 Uniformity The uniformity shall be determined visually or by other means at the time of use.

4.21 Storage Life. The storage life of the uncured prepreg shall be certified by the supplier.

4.22 Workmanship. The workmanship shall be determined visually or by other means at the time of use.

4.23 Preparation of Cured, Composite Laminated Test Specimens. The method of fabrication of the test specimens of cured, composite laminate shall be reported. All specimens shall be unidirectional. Tensile coupons shall consist of 6 plies of material, while all other specimens shall consist of 13 plies. A mean value for strength based on three specimens at RT for tensile, and 3 specimens at both RT and elevated temp (350° F) for longitudinal flex and interlaminar shear specimens, shall be reported.

4.23.1 Cured Thickness/Ply. The thickness of the cured laminates shall be measured in at least 5 representative locations using a flat-nosed micrometer to the nearest 0.0005 inch. The readings shall be averaged and divided by the number of plies; this value is the thickness/ply.

4.23.2 Flexural Strength (Ultimate) and Flexural Modulus.

a. Specimen dimensions shall be as shown in Figure 1. This thickness dimension (t) shall be in the range .0760 - .0840 inches. A variation in thickness over a specimen may not exceed .0060 inches.

b. The span length to thickness ratio shall be 32 $\pm$2 to 1. A load support method shall be utilized as shown in Figure 1.

c. The specimen shall be loaded to failure in a universal test machine capable of recording deflection at a load rate of 0.05 inch per minute.

d. Record the load at failure.

e. Calculations:

$$\text{Flexural Strength} = \frac{3Ps}{2w\ t^2}$$

$$\text{Flexural Modulus of Elasticity} = \frac{s^3M}{4w\ t^3}$$

P = the ultimate failure load in pounds to the nearest pound

s = the span length in inches to the nearest 0.005 inch

w = the specimen width in inches to the nearest 0.001 inch

t = the specimen thickness in inches to the nearest 0.0005 inch

M = the initial slope of the load-midspan deflection curve in pounds per inch

4.23.3 Tensile Strength (Ultimate) and Tensile Modulus.

a. Specimen dimensions shall be as shown in Figure 2. The thickness dimension (t) shall be in the range 0.0350-0.0390 inches. A variation in thickness over a specimen may not exceed 0.0060 inches.

b. The specimen shall be loaded to failure in a universal test machine, capable of recording axial strain by either strain gage or extensometer, at a load rate of .05 inch per minute.

c. Record the load at failure.

d. Calculations:

$$\text{Tensile strength} = \frac{P}{wt} = S_t$$

$$\text{Tensile Modulus} = \frac{S_t}{\delta}$$

P = the ultimate failure load on pounds to the nearest pound

w = the specimen width in inches to the nearest 0.001 inch

t = the specimen thickness in inches to the nearest 0.0005 inch

δ = the axial strain in inches per inch

4.23.4 Interlaminar Shear Strength

a. Specimen dimensions shall be as shown in Figure 3. The thickness dimension (t) will be in the range from .0760 to .0840 inches. A variation in thickness over a specimen may not exceed .0060 inches.

b. A load support method shall be utilized as shown in figure 3.

c. The specimen shall be loaded to failure in a universal test machine, at a load of 0.05 inch per minute.

d. Record the load at failure.

4.23.4 Interlaminar Shear Strength - (Continued)

3. Calculations: Interlaminar shear $F_{IS} = 3P/4wt$

P = load in pounds

w = specimen width in inches

t = specimen thickness in inches

4.23.5 Fiber Volume. (for Class 1 and Class 2; Class 3 to be determined) A specimen of approximately .25 x .6 x .080 shall be weighed in air (W_1), then weighed in gas free distilled water, to the nearest 0.001 gram (W_2) removing any bubbles adhering to the specimen. The specimen shall then be placed in concentrated (70 percent assay) nitric acid. Allow the specimen to digest until all fibers are completely separated, as determined visually. The fibers shall be removed and rinsed with additional nitric acid, then distilled water, and placed in an air circulating oven for 1 hour ± 5 min at 250 ±5° F. The fibers shall then be removed, cooled in a dessicator to ambient conditions and reweighed to the nearest 0.001 gram (W_3). The fiber volume in percent shall be $100\, W_3(W_1-W_2)/P_f\, W_1^2$ (where P_f is the fiber density from 4.2). The mean percent fiber volume shall be based on the average of three specimens.

4.24 Retest. If a material sample fails to meet the requirements of this specification due to preparation of test specimens, retest is permitted. The results of the original tests and the retest, and the reasons for failure. shall be included in the test report.

4.25 Rejection. Each batch of material shall be rejected if it does not pass the acceptance tests.

5. PREPARATION FOR DELIVERY

5.1 Packaging. Prepreg material shall be rolled on a reel of not less than 8 inches in diameter, or packaged in sheet form of a specified length and width. A nonadherent paper or polyethylene separator of a contrasting color shall be used on one side of the material, for rolls of tape, and on both sides of the material, for broadgoods, to prevent the layers of material from sticking to each other. Each roll or a specified number of sheets of prepreg shall be heat sealed in an evacuated, moisture-proof plastic bag. An identification tag shall be placed within each bag prior to sealing.

5.2 Packing. Units packaged as specified in 5.1 shall be packed in exterior-type shipping containers in a manner that (if refrigerated shipment is required by NR) will allow solid carbon dioxide to be packed in sufficient quantities to maintain a material temperature of 0° F, maximum, during transit. Upon receipt, containers shall be opened and examined to ascertain that solid carbon dioxide remains therein, if used. Prepreg rolls shall be packed in a horizontal position and containers so marked so as to insure horizontal positioning for shipment and later stored in an upright, vertical position. The shipping container shall be so constructed so as to assure safe delivery and acceptance at their destination. Shipping containers shall comply with carrier regulations applicable to the mode of transportation.

5.2.1 Marking of Shipment. Each shipping container and each roll or package of sheet prepreg shall be marked with the following information:

RESIN TREATED, GRAPHITE PREPREG, LOW PRESSURE MOLDING
NR SPECIFICATION NO. ST0130LB0005 TYPE CLASS GRADE
NR PURCHASE ORDER NO.
MANUFACTURER'S NAME, TRADEMARK OR SYMBOL
QUANTITY OF MATERIAL (i.e. No. of sheets of a certain width and length or width of roll and lineal feet)
MANUFACTURER'S BATCH AND LOT NO.
STORAGE TEMPERATURE, MAXIMUM 0° F
DATE OF MANUFACTURE
SHELF LIFE: 3 MONTHS AT 0° F
INSPECTION RECORD AND COMMENTS: Itemized descriptions of rejected material including square footage of such rejects, and their location.

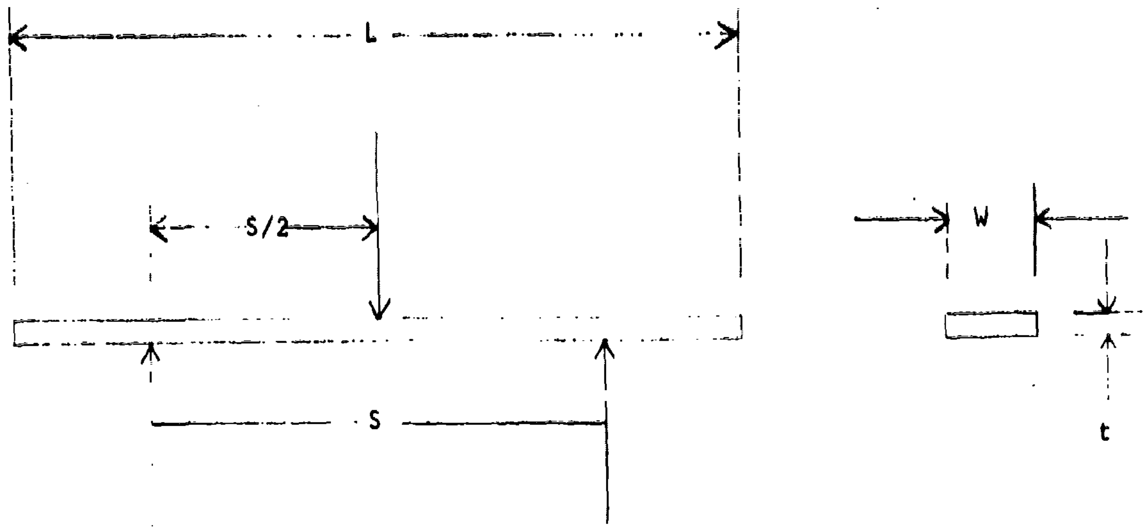
6. NOTES

6.1 Intended Use. The materials procured in accordance with this specification, when molded using low-pressure laminating methods, are suitable for use in airframe, aerospace and similarly related primary structural components where high stiffness and strength-to-weight ratios are required.

6.2 Drapability. If prepreg successfully passes this test, the test of prepreg tack will not be necessary.

6.3 Quality Conformance Tests. The supplier may obtain NR approval for alternate test methods in lieu of the methods specified in paragraphs 4.14 and 4.16.

LONGITUDINAL FLEXURE (0°)



LENGTH (L) = 4.0 ± 0.1
WIDTH (W) = 0.500 ± 0.003
THICKNESS (t) = 0.0760 - 0.0840

SPAN (S) = 2.50

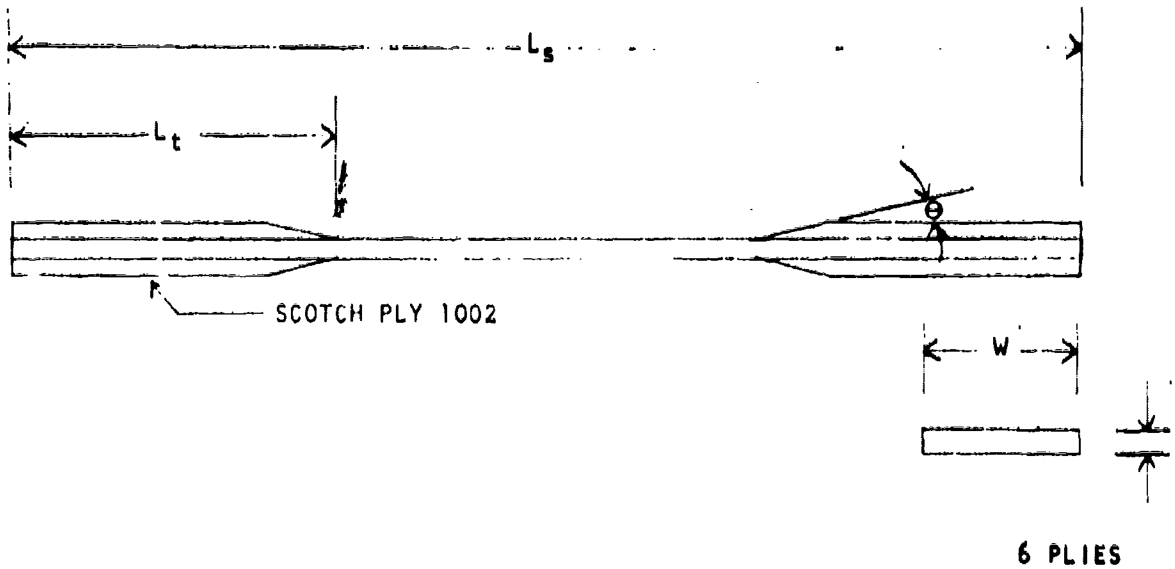
ALL TOWS SHALL BE 0° TO THE L DIMENSION.

LOAD AND REACTION SUPPORTS SHALL BE 1/8" RADIUS STEEL ROD.

ALL DIMENSIONS ARE IN INCHES.

Figure 1. Longitudinal Flexure Specimen (0°), Configurations and Loading Diagram

TENSILE COUPON

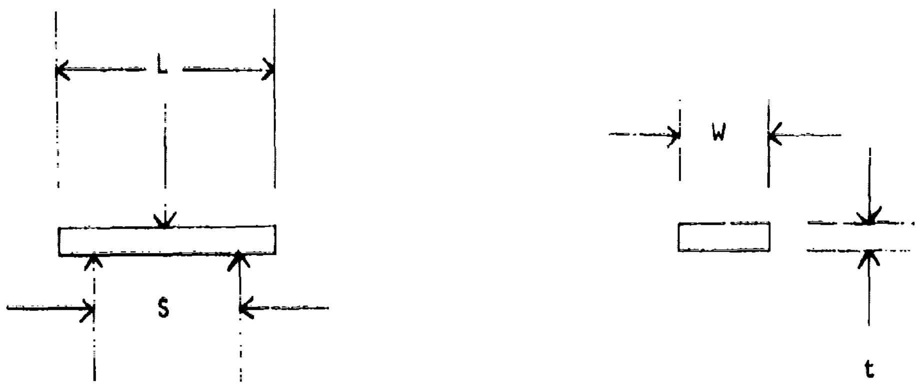


LENGTH (L_s)	= 9.0
LENGTH, TAB (L_t)	= 2.5
WIDTH (W)	= 0.875 ± .005
TAPER, TAB (Θ)	= 15°
THICKNESS	= 0.0350-0.0390

ALL TOWS TO BE 0° TO THE L DIMENSION
ALL DIMENSIONS ARE IN INCHES

Figure 2. Tensile Specimen, Configuration

INTERLAMINAR SHEAR (0°)



LENGTH (L) = 0.60 ± 0.01
WIDTH (W) = 0.250 ± .003
THICKNESS (t) = 0.0760 to 0.0840

SPAN (S) = 0.4 (OVERHAND MUST BE SAME OVER EACH END.)

LOAD AND REACTION SUPPORTS SHALL BE 1/8" RADIUS STEEL ROD.

ALL TOWS TO BE 0° TO THE L DIMENSION.

ALL DIMENSIONS ARE IN INCHES.

Figure 3. Interlaminar Shear Specimen (0°) Configuration and Loading Diagram

APPENDIX II

NR/LAD SPECIFICATION ST0105LA0013

ADVANCED COMPOSITES - FABRICATION

OF GRAPHITE/EPOXY COMPOSITE

LAMINATE PARTS OR COMPONENTS

PREPARED BY	CODE IDENT. NO. 43999	NUMBER
T. McGann	Los Angeles Division North American Rockwell	ST0105LA0013
APPROVALS		TYPE Process
		DATE 10 April 1972
	SPECIFICATION	SUPERSEDES SPEC. DATED:
		REV. LTR. New / PAGE 1 of 9

TITLE

ADVANCED COMPOSITES - FABRICATION OF GRAPHITE/EPOXY COMPOSITE LAMINATE PARTS OR COMPONENTS

TABLE OF CONTENTS

1. SCOPE

This specification establishes the procedures involved in the fabrication of thick and thin laminated parts or components utilizing graphite/epoxy pre-impregnated materials.

2. APPLICABLE DOCUMENTS

2.1 Document. The latest issues of the following documents form a part of this specification to the extent specified herein.

SPECIFICATION

North American Rockwell Corporation

ST0130LB0005	Advanced Composite Material - Graphite/Epoxy Prepreg, High Modulus, High Strength

3. REQUIREMENTS

3.1 Safety. This specification involves material or operations which may be hazardous. Coordinate with Industrial Hygiene and Safety regarding precautionary measures.

3.2 Materials. Materials shall be as follows:

Graphite/Epoxy Prepreg	ST0130LB0005
Glass Fabric 181 Dry	Commercial
Coroprene	Armstrong Cork
CW 1850 Mockburg Paper	West Coast Paper Co.
MS-122 Release Agent or Equivalent	Miller-Stephenson Chemical Co., Inc.
Methyl Ethyl Ketone	Commercial
Tedlar Film (2 Mil)	E.I.DuPont De Nemours & Co.
Vent Cloth, TX1040	Pallflex Products, Putham, Connecticut
Aluminum Foil Tape, Adhesive Backed	Commercial

3.3 Storage of Preimpregnated Materials. Graphite/Epoxy preimpregnated materials (ST0130LB0005) shall be stored in sealed plastic bags at temperatures not to exceed 0°F. Before use, the material shall be removed from storage and allowed to warm to room temperature before unsealing the plastic bag. A record of time in and time out of refrigeration shall be maintained and when accumulated time in 0°F storage exceeds three (3) months or time out of 0°F storage exceeds 10 days, the material shall be retested in accordance with 4.2. Any partially or fully laid up parts which must be stored shall be sealed in plastic bags at temperatures not exceeding 0°F. Upon removal from storage these parts shall be allowed to warm to room temperature before unsealing the plastic bag.

3.4 Manufacturing Documents. Manufacturing personnel shall have all applicable drawings and specifications and be thoroughly familiar with their contents before starting fabrication. A permanent manufacturing record shall be kept of each material lot received by Lot No. and number of batch length sheets or by Lot and continuous roll number for graphite prepreg material, together with the applicable part numbers and undivided serial numbers of all parts fabricated with the material.

3.5 Equipment.

3.5.1 Tooling. Tooling materials shall have a thermal expansion range compatible with the graphite/epoxy materials. In general, steel or titanium mold tooling is required to manufacture parts which meet all the engineering requirements affected by the tool.

3.5.2 Autoclave. The autoclave shall have a vacuum system capable of at least 25 inches of Hg, thermocouples with recording charts, a pressure regulator system capable of delivering 90-100 psig and a heater system capable of at least 350F.

3.5.3 Auxiliary Equipment. The following auxiliary equipment is required:

a) Scissors

b) "Stanley" knives

c) Teflon or polyethylene squeegee

d) Straight edges and squares

3.6 Fabrication

3.6.1 Lay-Up Environment. Lay-up shall be conducted in an area which has a controlled temperature of 60-75F, controlled humidity 30-75 percent and equipped with a filtering system to retain all particles 25 microns or larger.

3.6.2 Individual Ply Cutting. Individual plies shall be cut as follows:

a) Plies consisting of graphite/epoxy sheet material shall be cut utilizing metal templates and a "Stanley" knife.

b) Plies consisting of graphite/epoxy tape shall be cut utilizing mylar templates and scissors.

3.6.3 Preparation of Lay-Up Tool. Prepare the lay-up tool as follows:

a) Wipe the tool with clean cheesecloth, using MEK to remove all foreign material. Polish to develop a smooth surface. Wipe tool with a clean cheesecloth moistened with MEK and immediately wipe dry with another clean cheesecloth. Blow with clean, dry oil-free air or nitrogen to remove any traces of lint. Dip containers of solvent shall not be used.

b) Apply release agent to the tool mold surface per Manufacturer's instructions.

3.6.4 Lay-Up of Part. Lay-up the part as follows:

a) Position the first ply on the tool with the separator backing up. Plies consisting of two or more template cut pieces shall be butt type splices. Rub the ply with a squeegee to remove all air pockets and wrinkles. Remove the separator film.

b) Inspect the graphite prepreg ply lay-up in accordance with 3.6.5.

3.6.4 Lay-Up of Part. (Continued)

c) Repeat steps a and b until all of the required plies are laid up.

d) Uncured part lay-ups shall be stored in accordance with 3.3, unless the part is to be cured within 24 hours.

3.6.5 Individual Ply Inspection. Each ply shall be inspected as follows:

a) Gaps between graphite tows and ply butt splices shall not exceed 0.020 inch. NOTE: Graphite prepreg shall conform to the dimensional requirements of ST0130LB0005 within each sheet or tape.

b) Each ply shall be free of cured pieces of resin, crossed or broken tows and any other foreign material.

3.7 Preparation for Cure. The preparation for cure shall be as follows:

a) Cover the part with TX1040 vent cloth; trim the vent cloth to the net size of the part.

b) Locate 1 inch wide (minimum) coroprene boundary supports of the required thickness within 0.030 inch of the part edge to prevent fiber washing during resin flow. Boundary support material must have a minimum of 25 percent compressibility at 100 psig and be in accordance with paragraph 3.7.c. Corner joints in the boundary material must be sealed using a zinc chromate fillet to prevent loss of resin.

c) Boundary supports or dams for laminate lay-ups shall utilize coroprene; the height or thickness of the dam to be determined as follows:

$$Pn \times T_G = T_L$$

$$Tc = \frac{T_L}{0.7}$$

Pn = number of graphite/epoxy prepreg plies in laminate

T_G = cured thickness/ply of graphite/epoxy prepreg (inches)

T_L = thickness of cured laminate (inches)

Tc = required thickness of coroprene (inches)

3.7 Preparation for Cure. (Continued)

d) In all graphite prepreg laminates sufficient thermocouples shall be utilized to adequately record extreme variations in the anticipated part temperature. In addition, all laminates over 50 plies thick shall have at least one thermocouple placed at each of the following part locations: between laminate mid-plies, in the machining excess at the center of the laminate long edge; between the first and second ply of the CW1850 Mockburg Bleeder Paper at the center of the laminate edge. Thermocouples shall be iron constantan wire type. Thermocouple installation shall include removing the wire insulation and covering with zinc chromate where they cross the top of the dam, and that the laminate mid-ply thermocouple be placed parallel to the graphite tows.

e) Lay-up one ply of CW1850 Mockburg Paper for each 3 plies of graphite prepreg; this bleeder paper shall not extend beyond the periphery of the part.

f) Place a layer of Tedlar over the entire part; trim this to the net size of the part.

g) If caul plates are to be used, place an aluminum (0.060 inch) plate over the Tedlar.

h) Place another layer of Tedlar over the entire part so that the edges extend 1/2 inch beyond the periphery of the part; tape the Tedlar in place to the dams with adhesive backed aluminum foil tape.

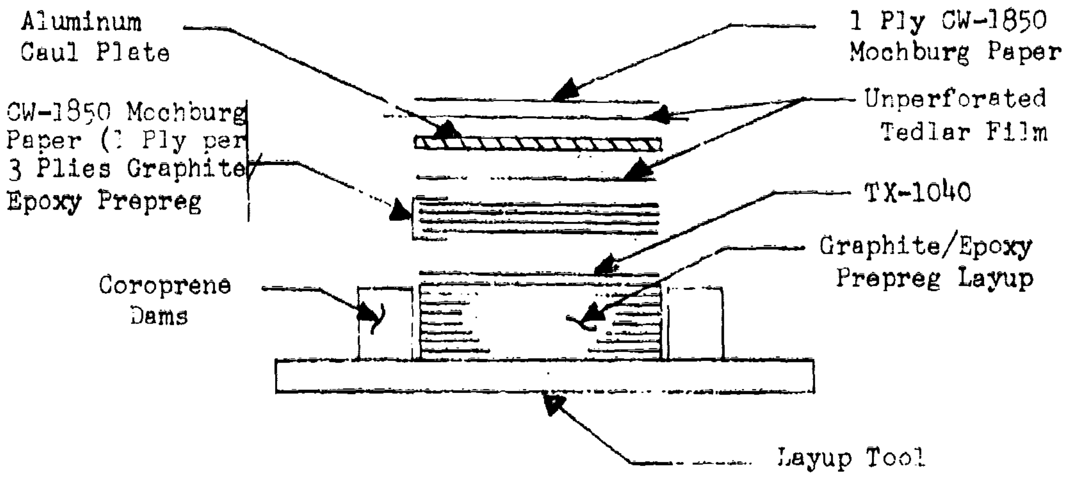
i) Place 1 ply of CW1850 Mockburg Paper on top, pre-cut to the size of the aluminum caul plate and tape in place, in order to properly seal the part periphery.

j) Cover the entire lay-up with 2 plies dry 181 glass fabric.

k) The entire lay-up shall be held securely against the tool by vacuum pressure during all subsequent handling until the part is in the autoclave for cure.

3.7 Preparation for Cure. (Continued)

1) The controlled-flow bleeder system is illustrated by the following sketch:



3.8 Cure. Cure graphite/epoxy parts as follows (3002 resin system only):

a) Hold under vacuum for $30 \, {}^{+15}_{-0}$ minutes, prior to installation in the autoclave.

b) Install the assembled lay-up in autoclave and perform vacuum leak check.

c) Raise part temperature to $250 \, {}^{+5}_{-10}$F in 27 ± 3 minutes (approximately 6.5F/minute) while maintaining vacuum pressure. NOTE: Part temperature is defined as the temperature of a 13 ply unidirectional laminate concurrently being cured with any other laminate part.(See 4.2)

3.8 Cure. (Continued)

d) Maintain vacuum pressure and part temperature of $250 \begin{smallmatrix}+5\\-10\end{smallmatrix}$F for 25 ± 5 minutes.

e) Raise autoclave pressure to 85 psig in 10 ± 2 minutes, vent the vacuum bag to atmospheric pressure at 20 - 30 psig.

f) Maintain 85 psig autoclave pressure and a part temperature of $250 \begin{smallmatrix}+10\\-5\end{smallmatrix}$F for 25 ± 5 minutes.

g) Raise part temperature from 250F to 350F in 15 ± 3 mins. (approximately 6.7F/minute).

h) Maintain 85 psig autoclave pressure and a part temperature of 350 ± 5F for 120 ± 10 minutes.

i) Maintain 85 psig autoclave pressure during part cool down to 125F or below as measured at the hottest area of any laminate part in the autoclave. The maximum to minimum temperature difference within any laminate shall not exceed 50F during cool down. Control laminate cool down by regulation of autoclave temperature as required.

j) Release the autoclave pressure after all laminates have cooled to 125F or below.

k) The part shall be post-cured in an air-circulating oven at 350 ± 5F for 120 ± 10 minutes. Support the part as necessary during post-cure to prevent laminate warpage.

3.9 Finished Parts. All finished parts shall meet the following requirements:

a) The thickness/ply shall not be less than 0.0056 nor greater than 0.0064 inches (See 4.5).

b) Visual inspection - see 4.4.

3.10 Packaging. The parts shall be wrapped in clean, heavy paper or plastic sheet, sealed, and labeled with the part number or other suitable identification. The wrapped parts shall be packed in suitable containers to prevent damage.

4. QUALITY ASSURANCE PROVISIONS

4.1 Surveillance. Minimum surveillance, control, and maintenance required to assure continued quality and consistency in manufacture shall be established.

4.2 Mechanical Property Requirements. A 13 ply unidirectional laminate, of such a size as to produce 6 longitudinal flexure and 6 interlaminar shear specimens, shall be concurrently cured with every part and shall meet the mechanical property requirements of ST0130LB0005 (see 3.4).

4.3 Retest of Graphite Impregnated Materials. Graphite impregnated materials which require retest shall meet the qualification inspection requirements for cured prepreg in accordance with ST0130LB0005 (see 3.4).

4.4 In-Process Lay-up Inspection. In-process lay-up inspection shall be made in accordance with 3.6.5.

4.5 Visual Inspection. All parts shall be visually inspected to insure compliance with Section 3. The cured part shall be closely observed on both surfaces and all items not acceptable shall be recorded on the planning sheet. The following are not acceptable:

a) Gaps between graphite tows in excess of 0.020 inch in width

b) Wrinkles

c) Contour

d) Dry areas

e) Delaminations

4.6 Determination of Part Thickness. The part shall be marked in a suitable grid pattern and measured for thickness. The thickness at each grid intersection shall be recorded on the planning sheet and accepted if within design limits. The laminate thickness shall fall between Tmin (minimum thickness) and Tmax (maximum thickness).

T_{min} = number of plies x .0056/ply

T_{max} = number of plies x .0064/ply

5. PREPARATION FOR DELIVERY - Not applicable

6. NOTES - Not applicable

APPENDIX III

NR/LAD IR&D GRAPHITE/EPOXY AMBIENT

AGING AND HUMIDITY ENVIRONMENT DATA

AMBIENT AGING AND HUMIDITY ENVIRONMENT COMPARISON

INTRODUCTION

The effects of ambient aging and humidity environment on uncoated, coated, and sealed graphite/epoxy laminate quality control properties were studied under an NR/LAD IR&D program. Furthermore, the effect of 6-month ambient aging on tension, compression, and in-plane shear strengths were examined. The basic test plan followed is shown in table LXXXIX, for Type AS/3002 treated graphite/epoxy. Table XC presents some initial exploratory data on Type A/3002 untreated graphite/epoxy.

Effect of Ambient Aging and Humidity Environment on Uncoated, Coated, and Sealed Laminate Quality Control Properties

Table XC, presents ambient aging data summarized for Type A/3002 batch untreated fiber quality control data. The room temperature tests showed no degradation even after 6 months for both the flexure and horizontal shear data. Elevated temperature data at 350°F, however, showed significant flexure and horizontal shear strength losses at 4 and 6 months ambient aging. An average strength loss of 43 percent for both the flexure and horizontal shear data was recorded.

Table XCI presents ambient and humidity environmental data for Type AS/3002 batch treated fiber. Tests were conducted at 300°F and showed the following trends.

1. Ambient Aging

   No significant degradation in flexure strength for ambient aging up to a period of 44 days (test date 6 Oct 1971) for both unsealed and polyurethane coated specimens. Horizontal shear strengths showed about a 12-percent degradation for both unsealed and coated specimens indicating that the polyurethane coating offered no protection.

2. Humidity environment (room temperature at 95% relative humidity)

   Aluminum foil sealed specimens after 44 days showed no significant degradation in flexure strength or horizontal shear and appear to offer a positive barrier to moisture penetration.

   Polyurethane coated specimens after 63 days showed a 15-percent and 29-percent strength reduction for longitudinal flexure and horizontal shear, respectively.

Unsealed specimens after 63 days showed an 8-percent and a 33-percent strength reduction for longitudinal flexure and horizontal shear, respectively.

TABLE LXXXIX. AMBIENT AGING PROGRAM TYPE AS/3002 BATCH TREATED

Type of Test	Configuration	Laminate Orientations	Total Replicates	Test Temperature	Aging Factor	Total Specimens
Longitudinal flexure	Quality control	$[0]_{13}$	3	300°F after 1/2 hr soak	*	24
Horizontal shear	Quality control	$[0]_{13}$	3	300°F after 1/2 hr soak	*	24
Tension	IITRI	$[0]_6$ and $[0/\pm45/90]_S$	2	RT & 265°F after 1/2 hr soak	180 days ambient	4
Compression	Honeycomb beam	$[0]_6$ and $[0/\pm45/90]_S$	2	RT & 265°F after 1/2 hr soak	180 days ambient	4
Shear	Rail shear	$[0]_6$ and $[0/\pm45/90]_S$	2	RT & 265°F after 1/2 hr soak	180 days ambient	4

*3 control specimens (ambient) plus 3 ambient specimens weighed periodically.

3 sealed in aluminum bag placed in humidity chamber and weighed and tested at same time "1% weight gain" specimens tested

9 specimens unsealed placed in humidity chamber and tested after 0.1%, 0.5% and 1.% weight gain.
3 with polyurethane coating (humidity chamber) plus 3 "ambient aged" specimens tested at same time "1.% weight gain" specimen tested.

TABLE XC. AMBIENT AGING STUDY GRAPHITE/EPOXY
TYPE A/3002 BATCH UNTREATED FIBER

Test	Control		4 Months		6 Months	
	Temp RT	Temp 350°F	Temp RT	Temp 350°F	Temp RT	Temp 350°F
*Longitudinal flexure (Ksi)	258	182	241	98.3	239	109
Test/control	1.00	1.00	0.934	0.541	0.926	0.600
*Horizontal shear (Ksi)	8.44	7.59	9.19	4.25	10.49	4.36
Test/control	1.00	1.00	1.089	0.560	1.243	0.574

*Average of three values

TABLE XCI. AMBIENT AND HUMIDITY ENVIRONMENTAL DATA - GRAPHITE/EPOXY (TYPE AS/3002 BATCH TREATED FIBER)

Test	Control	Ambient Aging		Humidity (RT at 98% RH)				
		Unsealed	Coated**	Unsealed	Unsealed	Unsealed	Coated**	Sealed***
	8-24-71	10-6-71	10-6-71	8-26-71	9-7-71	10-6-71	10-6-71	10-6-71
Weight gain %	0	0.15-0.17	0.0-0.2	0.1+	0.5	0.87-0.99	0.81-0.90	0.01-0.02
*Longitudinal flexure (Ksi)	219	215	206	226	242	201	186	207
Test/control	1.00	0.982	0.941	1.032	1.105	0.918	0.849	0.945
Weight gain %	0	0.06-0.14	-0.11-0.23	0.1+	0.5	1.08-1.16	0.61-0.86	-0.03-0.10
*Horizontal shear (Ksi)	10.18	9.13	8.96	10.05	9.64	6.85	7.24	9.51
Test/control	1.00	0.897	0.880	0.987	0.947	0.673	0.711	0.934

NOTE: Test temperature = 300°F

*Average of three values

**Polyurethane

***Aluminum foil

EFFECTS ON TENSION, COMPRESSION AND SHEAR PROPERTIES

Table XCII contains tension data for 6-month ambient aged graphite/epoxy (Type AS/3002 batch treated) IITRI coupon tests. The $[0]_{6T}$ and $[0/\pm45/90]_S$ laminate orientations were tested at both room temperature and 265°F. The room temperature test strengths both compared well with strength values for unexposed specimens (no ambient aging). Also, the 265°F test strengths were within 10 percent of the room temperature controls. The general conclusion then, is that ambient aging has little effect on tension strength of Type AS/3002 batch graphite/epoxy laminates.

Table XCIII presents sandwich compression bending beam data for $[0]_{6T}$ and $[0/\pm45/90]_S$ Type AS/3002 batch (treated) graphite/epoxy laminates which were ambient aged for 6 months (180 days) prior to testing. Room temperature and 265°F tests were conducted for both orientations tested. In general, the room temperature compression strengths compared well with specimens which were not ambient aged, hence indicating no degradation due to the 6-month ambient aging. The 265°F test values also seemed to show no degradation as they were not much lower than the room temperature test values (which showed little or no degradation). Compression properties, then, seem unaffected by ambient aging up to 6 months.

Room temperature and 265°F rail (in-plane) shear test data for Type AS/3002 batch (treated) graphite/epoxy specimens, previously ambient aged for 6 months, are presented in table XCIV. The $[0]_{6T}$ and $[0/\pm45/90]_S$ laminate orientations were tested. Note that the room temperature $[0]_{6T}$ specimen was not tested due to a pretest crack discovered during inspection. The room temperature $[0/\pm45/90]_S$ laminate test exceeded the control value (no ambient aging) by 19 percent, hence indicating no degradation. No ambient aging problem is indicated for room temperature in-plane shear strengths. Furthermore, since the 265°F in-plane shear strength for the $[0/\pm45/90]_S$ laminate exceeded the room temperature control, it could be assumed that the ambient aging caused no strength degradation at 265°F.

TABLE XCII. TENSION DATA FOR 6-MONTH AMBIENT AGED IITRI COUPONS GRAPHITE/EPOXY (TYPE AS/3002 BATCH)

Specimen No.	Orientation	Thickness (in.)	W Width (in.)	Temp (°F)	Max Load (lb)	Stress (Ksi)	Test Stress/ Control*
T-ULAA-1	$[0]_{6T}$	0.0366	0.7365	RT	4,750	176.21	1.21
T-ULAA-2	$[0]_{6T}$	0.0356	0.7376	265	3,455	131.58	---
T-8LAA-1	$[0/\pm45/90]_S$	0.0465	0.7412	RT	2,130	61.80	1.14
T-8LAA-2	$[0/\pm45/90]_S$	0.0484	0.7317	265	2,075	58.60	---

*Control stress from tension coupons without ambient aging exposure

TABLE XCIII. COMPRESSION DATA FOR 6-MONTH AMBIENT AGED SANDWICH BENDING BEAM GRAPHITE/EPOXY (TYPE AS/3002 BATCH)

Specimen No.	Orientation	Thickness (in.)*	w Width (in.)	Temp (°F)	Max Load (lb)	Stress (Ksi)	Test Stress/ Control**	Failure Mode***
CLBB-ULAA-1	$[0]_{6T}$	0.036	1.014	RT	2,700	189.90	1.11	D, CS
CLBB-ULAA-2	$[0]_{6T}$	0.036	1.006	265	2,570	182.19	---	D
CLBB-8LAA-1	$[0/\pm45/90]_S$	0.048	1.004	RT	1,760	93.40	0.97	C
CLBB-8LAA-2	$[0/\pm45/90]_S$	0.048	1.006	265	1,550	82.10	---	D

*Nominal face sheet thickness

**Control stress from bending beam tests without ambient aging exposure

***Failure mode code:

C = face sheet compression failure; CS = core shear; D = face sheet delamination

TABLE XCIV. RAIL SHEAR DATA FOR 6-MONTH AMBIENT AGED SPECIMENS GRAPHITE/EPOXY (TYPE AS/3002 BATCH)

Specimen No.	Orientation	Temp (°F)	Thickness (in.)	Length L (in.)	Width w (in.)	Max Load (lb)	Shear Stress (Ksi)	Test Stress/ Control*
RS-ULAA-1	$[0]_{6T}$	RT	0.036	8.025	3.870	**	**	---
RS-ULAA-2	$[0]_{6T}$	265	0.037	8.020	3.875	1,770	5.97	---
RS-8LAA-1	$[0/\pm45/90]_S$	RT	0.050	8.015	***	16,750	41.80	1.19
RS-8LAA-2	$[0/\pm45/90]_S$	265	0.049	8.035	3.865	14,875	37.78	---

*Control values were rail shear specimens which were not ambient aged
**Specimen was not tested as pretest cracks were noted during inspection
***Width varied from 3.864 to 3.833 inches

APPENDIX IV

ERRATA

FOR VOLUMES I AND III

INTRODUCTION

The purpose of this appendix is to furnish errata for Volumes I and III in the following defined areas:

Area 1 - Volume III, Section VII, "Thermoelastic Relationships," pp 91-97

Area 2 - Volume III, Computer Program Deck AC-40, "N-Ply Laminate Thermoelastic Analysis," pp 209-218

Area 3 - Volume I, subsection entitled, "Thermal Expansion - Macromechanics," pp 218-222

Area 4 - Volume III, subsection entitled, "D_{ij}'s of Some Commonly Used Laminates," pp 11-15

It is recommended that marginal notations be made in Volumes I and III in each of these areas referring to this appendix for corrected information. As an aid to correlation, each page in this appendix will indicate, adjacent to the page number, the original page it replaces.

In area 1, an error was detected in the $[B]_i$ matrix, equation 142, which affects not only the rest of the section but areas 2 and 3 as well. All affected pages have been corrected and are presented in the following sections of this appendix. In addition, during the process of making the corrections, advantage was taken of the opportunity to make the following changes:

- Computer Program AC-40 can now be used for any lamina material, even when the laminate is composed of mixed laminae.

- Specific curves for B/Ep laminates at 350° F have been added to area 3.

- In area 1, even though the existing analysis approach was valid, it has been changed to increase visibility.

In area 4, the subsection entitled "D_{ij}'s of Some Commonly Used Laminates" has been revised to correct a typographical error in equation 24. The corrected pages are incorporated in this appendix. Computer program AC-2 which performs the analytical calculations was correct, however, and consequently needed no revision.

AREA 1

SECTION VII

THERMOELASTIC RELATIONSHIPS

In this analysis, it is assumed that the elastic and thermal response of each ply of an N-ply laminate is known. The quantities specifying the elastic and thermal response of a ply may be obtained from the data presented in volume I. The thermoelastic stress-strain relation for the i^{th} layer in a state of plane stress (stress components normal to the L-T plane are zero) is given by

$$\begin{Bmatrix} \sigma_L \\ \sigma_T \\ \sigma_{LT} \end{Bmatrix}_i = \begin{bmatrix} T_{11} & T_{12} & 0 \\ T_{12} & T_{22} & 0 \\ 0 & 0 & T_{33} \end{bmatrix}_i \begin{Bmatrix} \epsilon_L - \alpha_L \Delta T \\ \epsilon_T - \alpha_T \Delta T \\ \gamma_{LT} \end{Bmatrix}_i$$

where

$$\left.\begin{aligned} T_{11} &= E_L \Big/ \left(1 - \nu_{LT}\,\nu_{TL}\right) = E_L\, T_{22} \Big/ E_T \\ T_{12} &= \nu_{TL}\, E_L \Big/ \left(1 - \nu_{LT}\,\nu_{TL}\right) = \nu_{LT}\, E_T \Big/ \left(1 - \nu_{LT}\,\nu_{TL}\right) \\ T_{33} &= G_{LT} \\ \gamma_{LT} &= 2\,\epsilon_{LT} \end{aligned}\right\} \qquad (138)$$

Figure 43 shows the laminate in question.

Here, ν_{TL} denotes the magnitude of the strain in the longitudinal direction due to a unit strain in the transverse direction; ν_{LT} denotes the magnitude of the strain in the transverse direction due to a unit strain in the longitudinal direction.

To obtain the stress-strain relations for a lamina for the case where the applied stress makes an angle θ_i to the natural lamina axis, equation 138 must be subjected to a coordinate transformation. The case under consideration is illustrated in figure 44.

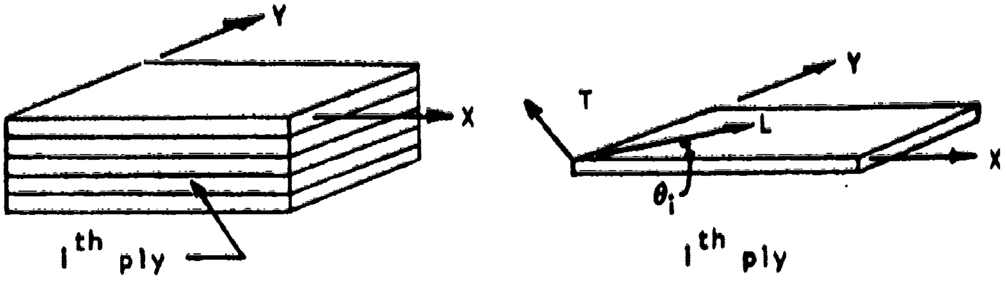


Figure 43. Coordinates of i^{th} Ply in Natural Lamina and Laminate Systems

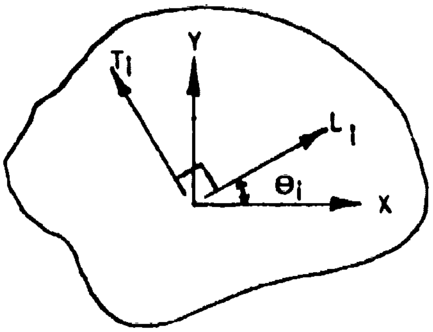


Figure 44. Relationship Between Laminae and Laminate Coordinate Systems

The stress-strain relations for the typical i^{th} ply of the laminate shown in figure 43 is assumed to be of the form

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix}_i = \begin{bmatrix} B \end{bmatrix}_i \begin{Bmatrix} \epsilon_x - \alpha_x \Delta T \\ \epsilon_y - \alpha_y \Delta T \\ \gamma_{xy} - \alpha_{xy} \Delta T \end{Bmatrix}_i \tag{139}$$

or $$\left\{ \sigma \right\}_i = \begin{bmatrix} B \end{bmatrix}_i \left\{ \epsilon \right\}_i - \begin{bmatrix} B \end{bmatrix}_i \left\{ \alpha \right\}_i \Delta T$$

where the matrix $[B]_i$ of order 3 x 3 is yet to be determined. It is well known that the ply stress and strain components transform from one coordinate system (X, Y, Z) to another coordinate system (L, T, Z) according to the transformation law of a tensor of order two (reference 1). Hence,

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix}_i = \begin{bmatrix} D \end{bmatrix}_i \begin{Bmatrix} \sigma_L \\ \sigma_T \\ \sigma_{LT} \end{Bmatrix}_i , \quad \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_{xy} \end{Bmatrix}_i = \begin{bmatrix} D \end{bmatrix}_i \begin{Bmatrix} \epsilon_L \\ \epsilon_T \\ \epsilon_{LT} \end{Bmatrix}_i , \quad \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \frac{\alpha_{xy}}{2} \end{Bmatrix} = \begin{bmatrix} D \end{bmatrix}_i \begin{Bmatrix} \alpha_L \\ \alpha_T \\ \frac{\alpha_{LT}}{2} \end{Bmatrix}_i$$

and performing the matrix maniuplations, we find that (140)

$$\begin{Bmatrix} \alpha_L \\ \alpha_T \\ \alpha_{LT} \end{Bmatrix}_i = \begin{bmatrix} D \end{bmatrix}_i^T \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{Bmatrix}_i , \quad \begin{Bmatrix} \epsilon_L \\ \epsilon_T \\ \gamma_{LT} \end{Bmatrix}_i = \begin{bmatrix} D \end{bmatrix}_i^T \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix}_i$$

where

$$[D]_i = \begin{bmatrix} m_i^2 & n_i^2 & -2\,m_i n_i \\ n_i^2 & m_i^2 & 2\,m_i n_i \\ m_i n_i & -m_i n_i & m_i^2 - n_i^2 \end{bmatrix} \tag{141}$$

and $\quad n_i = \sin\theta_i, \quad m_i = \cos\theta_i$

Substituting equation 140 into 138 and performing the appropriate matrix manipulations, we find that $[B]_i$ of equation 139 is

$$[B]_i = [D]_i \quad [T]_i \; [D]_i^T \tag{142}$$

By performing the indicated multiplication for equation 142, it is found that the elements of the $[B]_i$ matrix are

$$B_{11} = T_{11}m^4 + 2\,(T_{12} + 2\,T_{33})\,m^2n^2 + T_{22}n^4$$

$$B_{12} = (T_{11} + T_{22} - 4T_{33})m^2n^2 + T_{12}\,(m^4 + n^4) = B_{21}$$

$$B_{13} = (T_{11} - T_{12} - 2T_{33})nm^3 + (T_{12} - T_{22} + 2\,T_{33})\,n^3m = B_{31} \tag{143}$$

$$B_{22} = T_{11}\,n^4 + 2\,(T_{12} + 2\,T_{33})\,n^2m^2 + T_{22}m^4$$

$$B_{23} = (T_{11} - T_{12} - 2T_{33})\,n^3m + (T_{12} - T_{22} + 2\,T_{33})\,nm^3 = B_{32}$$

$$B_{33} = (T_{11} + T_{22} - 2T_{12} - 2T_{33})\,n^2m^2 + T_{33}\,(m^4 + n^4)$$

We will now consider a laminate consisting of n plies with natural axes making various angles θ_i, with respect to the reference (X, Y) axes of the laminate. We impose the restriction that the plies are arranged symmetrically with respect to the center plane of the laminate. Because of this restriction, there is no coupling between in-plane loading and out-of-plane deformations.

The laminate plate shown in figure 43 is assumed to be subjected to applied stresses (in-plane) and temperature changes (uniform) which do not result in curvature of the plies. For a laminate of thickness t, the stress resultants are defined by

$$N_x = \int_{-t/2}^{t/2} \sigma_x \, dz, \qquad N_y = \int_{-t/2}^{t/2} \sigma_y \, dz, \qquad N_{xy} = \int_{-t/2}^{t/2} \sigma_{xy} \, dz \tag{144}$$

Integrating equation 139 across the laminate thickness and assuming the stress components to be constant across each lamina and the strain components not to vary with z, we obtain

$$\{N\} = [\bar{B}] \{\epsilon\} - \Delta T \{C\} \tag{145}$$

where

$$N_x = \sum_{i=1}^{n} \sigma_{x_i} h_i, \qquad N_y = \sum_{i=1}^{n} \sigma_{y_i} h_i, \qquad N_{xy} = \sum_{i=1}^{n} \sigma_{xy_i} h_i$$

$$\bar{B}_{jk} = \sum_{i=1}^{n} \left(B_{jk}\right)_i h_i \tag{146}$$

$$C_x = \sum_{i=1}^{n} \left(\alpha_x B_{11} + \alpha_y B_{12} + \alpha_{xy} B_{13}\right)_i h_i$$

$$C_y = \sum_{i=1}^{n} \left(\alpha_x B_{21} + \alpha_y B_{22} + \alpha_{xy} B_{23} \right)_i h_i$$

$$C_{xy} = \sum_{i=1}^{n} \left(\alpha_x B_{31} + \alpha_y B_{32} + \alpha_{xy} B_{33} \right)_i h_i \tag{146}$$

and h_i denotes the thickness of the i^{th} ply.

The coefficients of thermal expansion α_x^c, α_y^c, α_{xy}^c for the n-ply laminate are obtained from equation 145 by setting the applied in-plane resultants equal to zero. Hence,

$$\begin{Bmatrix} \alpha_x^c \\ \alpha_y^c \\ \alpha_{xy}^c \end{Bmatrix} = \left\{ \alpha^c \right\} = \frac{\{\epsilon\}}{\Delta T} = \left[\bar{B} \right]^{-1} \left\{ C \right\} \tag{147}$$

Then the general stress-strain relation for an n-layered laminate subjected to extensional deformation takes on the form

$$\left\{ N \right\} = \left[\bar{B} \right] \left\{ \epsilon \right\} - \left[\bar{B} \right] \left\{ \alpha \right\} \Delta T = \left[\bar{B} \right] \left\{ \epsilon - \alpha^c \, \Delta T \right\} \tag{148}$$

Therefore, for any combination of applied in-plane loadings and uniform temperature changes, the corresponding strain field for the laminate is obtained from equation 148.

$$\begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} = \left\{ \epsilon \right\} = \left[\bar{B} \right]^{-1} \left\{ N \right\} + \Delta T \left\{ \alpha^c \right\} = \left\{ \epsilon \right\}_i, \text{ for } i = 1, 2, \cdots N \tag{149}$$

To calculate the stresses in the i^{th} ply due to the strain field of equation 149 for all plies, equation 138 is employed; hence,

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{Bmatrix}_i = \begin{bmatrix} B \end{bmatrix}_i \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} - \begin{bmatrix} B \end{bmatrix}_i \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{Bmatrix}_i \Delta T \tag{150}$$

These stresses are in the direction of the laminate reference axes X, Y. The stresses in each ply with respect to the natural axes of the ply are obtained from

$$\begin{Bmatrix} \sigma_L \\ \sigma_T \\ \sigma_{LT} \end{Bmatrix}_i = \begin{bmatrix} T \end{bmatrix}_i \begin{bmatrix} D \end{bmatrix}_i^T \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} - \begin{bmatrix} T \end{bmatrix}_i \begin{bmatrix} D \end{bmatrix}_i^T \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{Bmatrix}_i \Delta T \tag{151}$$

For the case when only a uniform temperature change is present, we find from equations 149 and 151 that the i^{th} ply stresses become

$$\begin{Bmatrix} \sigma_L \\ \sigma_T \\ \sigma_{LT} \end{Bmatrix}_i = \begin{bmatrix} T \end{bmatrix}_i \begin{bmatrix} D \end{bmatrix}_i^T \left[\begin{Bmatrix} \alpha_x^c \\ \alpha_y^c \\ \alpha_{xy}^c \end{Bmatrix} - \begin{Bmatrix} \alpha_x \\ \alpha_y \\ \alpha_{xy} \end{Bmatrix}_i \right] \Delta T \tag{152}$$

or the ply stresses in its natural coordinate system are proportional to the differences between the laminate coefficients of thermal expansion, as defined by equation 147, and the ply coefficients of thermal expansion.

A computer program, AC-40, has been written to perform these calculations for $\{\alpha^c\}$ for any crossplied laminates. The program listing and sample data and output sheets are presented in another section of volume III. Correlations of this theory with available test data and typical design curves are described in volume I of this report.

AREA 2

ADVANCED FILAMENTARY COMPOSITE MECHANICAL PROPERTIES COMPUTER PROGRAM DECK NO. AC-40

ABSTRACT

This program calculates the thermal stresses and coefficients of thermal expansion in both the individual ply axes and the laminate axes, given the macromechanical properties of each ply.

PROGRAM INPUT DATA

The data are described as follows:

Card A:

- NM = No. of materials
  Option (not initial case): NM = 0 uses material data for previous case
- NL = No. of plies
- DT = Temperature increment in degrees F

Card(s) B: One card for each material, leave out IFF NM = 0

- EL = Lamina longitudinal modulus - psi
- ET = Lamina transverse modulus - psi
- GLT = Lamina shear modulus - psi
- ALPHAL = Lamina longitudinal coefficient thermal expansion - in./in./°F
- ALPHAT = Lamina transverse coefficient thermal expansion - in./in./°F
- ULT = Lamina Poisson's ratio - in./in.
- T = Lamina thickness - in.

Cards(s) C:

- M(I) = Material of the i^{th} layer
- THETA(I) = Angle of the i^{th} layer

Note that only one "set" of a laminate need be coded in. For example, for a $(0/\pm 60/90_2)_{3S}$ laminate, only the 0°, +60°, -60°, 90°, and 90° plies need be input, giving a total NL of five plies.

OUTPUT

The output consists of the DI, B, α, and $\bar{B}$ matrices; the coefficients of thermal expansion in the laminate axes $\bar{\alpha}_x$, $\bar{\alpha}_y$, and $\bar{\alpha}_{xy}$; and the thermal stresses in the laminates axes, σ_x, σ_y, and σ_{xy}, plus the thermal stresses in the individual ply natural axes, σ_L, σ_T, and σ_{LT}.

The output is shown on the sample output pages following the text.

```
BPS FORTRAN D COMPILER
C      PROGRAM AC40...N-PLY LAMINATE THERMOELASTIC ANALYSIS PROGRAM
C
C      INPUT DATA IS AS FOLLOWS.....
C
C                     NL = NUMBER OF PLIES (NO MAXIMUM)
C                     NM = NUMBER OF MATERIALS (20 MAXIMUM)
C                     DT = TEMPERATURE INCREMENT IN DEGREES F
C
C                  EL,ET = LONGITUDINAL AND TRANSVERSE YOUNG'S MODULI - PSI
C                    GLT = SHEAR MODULUS - PSI
C          ALPHAL,ALPHAT = LONGIT. & TRANS. COEFF. OF THERMAL EXPANSION
C                    ULT = POISSON'S RATIO LT
C                      T = THICKNESS PER PLY  - IN.
C
C                   M(I) = MATERIAL OF THE LAYER I
C               THETA(I) = THETA OF LAYER I
C
      DIMENSION EL(20),ET(20),GLT(20),ULT(20),UTL(20),AL(20),AT(20),
     1   H(20),A(20,3,3),SL(20),ST(20),SLT(20),TH(20)
      DIMENSION T(20,3,3),EM(20),EN(20),B(20,3,3),DI(20,3,3),AX(20),
     1   AXY(20),BB(3,3),SX(20),SY(20),SXY(20),BI(3,3),AY(20)
      DIMENSION D(20,3,3)
      DIMENSION ELP(7,20),M(20)
      EQUIVALENCE (D(1),DI(1))
    5 READ(5,1)NM,NL,DT
    1 FORMAT(2I12,F12.0)
      IF(NM)7,7,4
    4 DO 3 N=1,NM
      READ(5,2) (ELP(I,N),I=1,7)
    2 FORMAT(5F12.0,2F6.0)
    3 CONTINUE
    7 DO 100 IS=1,NL,6
C PROPERTIES OF INDIVIDUAL LAMINA
      IE=MIN0(IS+5,NL)
C TH(I) = ANGLE BETWEEN NATURAL AXES OFI-TH PLY AND LAMINATE AXES
      READ(5,6) (M(I),TH(I),I=IS,IE)
    6 FORMAT(6(I6,F6.0))
      DO 100 I=IS,IE
C CALCULATE ELEMENTS OF T MATRIX
      MP=M(I)
      EL(I)=ELP(1,MP)
      ET(I)=ELP(2,MP)
      GLT(I)=ELP(3,MP)
      ULT(I)=ELP(6,MP)
      AL(I)=ELP(4,MP)
      AT(I)=ELP(5,MP)
      H(I)=ELP(7,MP)
      UTL(I)=ULT(I)*ET(I)/EL(I)
   46 T(I,1,1)=EL(I)/(1.-ULT(I)*UTL(I))
      T(I,1,2)=EL(I)*UTL(I)/(1.-ULT(I)*UTL(I))
      T(I,1,3)=0.
      T(I,2,1)=T(I,1,2)
      T(I,2,2)=ET(I)/(1.-ULT(I)*UTL(I))
      T(I,2,3)=0.
      T(I,3,1)=0.
      T(I,3,2)=0.
      T(I,3,3)=GLT(I)
```

```
C CALCULATE ELEMENTS OF B MATRIX
      EM(I)=COSD(TH(I))
      EN(I)=SIND(TH(I))
   50 B(I,1,1)=T(I,1,1)*EM(I)**4+2.*(T(I,1,2)+2.*T(I,3,3))*(EM(I)**2)*
     1(EN(I)**2)+T(I,2,2)*EN(I)**4
      B(I,1,2)=(T(I,1,1)+T(I,2,2)-4.*T(I,3,3))*(EM(I)**2)*(EN(I)**2)+T(I
     1,1,2)*(EM(I)**4+EN(I)**4)
      B(I,1,3)=(T(I,1,1)-T(I,1,2)-2.*T(I,3,3))*EN(I)*EM(I)**3+(T(I,1,2)-
     1T(I,2,2)+2.*T(I,3,3))*EM(I)*EN(I)**3
      B(I,2,2)=T(I,1,1)*EN(I)**4+2.*(T(I,1,2)+2.*T(I,3,3))*(EN(I)**2)*
     1(EM(I)**2)+T(I,2,2)*EM(I)**4
      B(I,2,3)=(T(I,1,1)-T(I,1,2)-2.*T(I,3,3))*EM(I)*EN(I)**3+(T(I,1,2)-
     1T(I,2,2)+2.*T(I,3,3))*EN(I)*EM(I)**3
      B(I,3,3)=(T(I,1,1)+T(I,2,2)-2.*T(I,1,2)-2.*T(I,3,3))*(EN(I)**2)*
     1(EM(I)**2)+T(I,3,3)*(EM(I)**4+EN(I)**4)
      B(I,2,1)=B(I,1,2)
      B(I,3,1)=B(I,1,3)
      B(I,3,2)=B(I,2,3)
C   CALCULATE ELEMENTS OF D MATRIX
   70 DI(I,1,1)=EM(I)**2
      DI(I,1,2)=EN(I)**2
      DI(I,1,3)=-2.* EM(I)*EN(I)
      DI(I,2,1)=DI(I,1,2)
      DI(I,2,2)=DI(I,1,1)
      DI(I,2,3)=-DI(I,1,3)
      DI(I,3,1)=DI(I,2,3)/2.
      DI(I,3,2)=DI(I,1,3)/2.
   80 DI(I,3,3)=EM(I)**2-EN(I)**2
C CALCULATE ELEMENTS OF ALPHA MATRIX
      AX(I)=DI(I,1,1)*AL(I)+DI(I,2,1)*AT(I)
      AY(I)=DI(I,1,2)*AL(I)+DI(I,2,2)*AT(I)
   90 AXY(I)=-DI(I,1,3)*AL(I)-DI(I,2,3)*AT(I)
  100 CONTINUE
      WRITE(6,700)
  700 FORMAT(1H1,25X,'N-PLY LAMINATE THERMOELASTIC ANALYSIS'//,2X,'N',
     111X,'EL',12X,'ET',11X,'GLT',6X,'ULT',7X,'UTL',8X,'ALPHAL',8X,
     2'ALPHAT',9X,'H')
      DO 702 N=1,NM
      UTP=ELP(6,N)*ELP(2,N)/ELP(1,N)
      WRITE(6,701)N,(ELP(I,N),I=1,3),ELP(6,N),UTP,(ELP(I,N),I=4,5)
     1,ELP(7,N)
  701 FORMAT(1H I2,3F14.0,2F10.4,2F14.8,F10.4)
  702 CONTINUE
      WRITE(6,703)
  703 FORMAT(1H05('LAYER   N   THETA      '))
      DO 705 NS=1,NL,5
      NE=MIN0(NS+4,NL)
      WRITE(6,704) (N,M(N),TH(N),N=NS,NE)
  704 FORMAT(1H 5(I5,I3,F7.1,5X))
  705 CONTINUE
      WRITE(6,710)(I,DI(I,1,1),DI(I,1,2),DI(I,1,3),I,DI(I,2,1),DI(I,2,2)
     1,DI(I,2,3),I,DI(I,3,1),DI(I,3,2),DI(I,3,3),I=1,N)
  710 FORMAT(1H0,30X,23HELEMENTS OF D  MATRIX  ///(10X,I2,5X,E17.8,5X,E1
     17.8,5X,E17.8))
      WRITE(6,720)(I,B(I,1,1),B(I,1,2),B(I,1,3),I,B(I,2,1),B(I,2,2),B(I,
     12,3),I,B(I,3,1),B(I,3,2),B(I,3,3),I=1,N)
  720 FORMAT(1H0,30X,22HELEMENTS OF B MATRIX  ///(10X,I2,5X,E17.8,5X,E17
     1.8,5X,E17.8))
      WRITE(6,740)(I,AX(I),AY(I),AXY(I),I=1,N)
  740 FORMAT(1H0,30X,26HELEMENTS OF ALPHA MATRIX  ///(10X,I2,5X,E17.8,5X
     1,E17.8,5X,E17.8))
```

```
C CALCULATE PROPERTIES OF N-PLY LAMINATE
C CALCULATE ELEMENTS OF B-BAR MATRIX
      BB(1,1)=0.
      BB(1,2)=0.
      BB(1,3)=0.
      BB(2,1)=0.
      BB(2,2)=0.
      BB(2,3)=0.
      BB(3,1)=0.
      BB(3,2)=0.
      BB(3,3)=0.
  120 DO 200 I=1,N
      DB1=B(I,1,1)*H(I)
      BB(1,1)=BB(1,1)+DB1
      DB2=B(I,1,2)*H(I)
      BB(1,2)=BB(1,2)+DB2
      DB3=B(I,1,3)*H(I)
      BB(1,3)=BB(1,3)+DB3
  140 DB4=B(I,2,1)*H(I)
      BB(2,1)=BB(2,1)+DB4
      DB5=B(I,2,2)*H(I)
      BB(2,2)=BB(2,2)+DB5
      DB6=B(I,2,3)*H(I)
      BB(2,3)=BB(2,3)+DB6
      DB7=B(I,3,1)*H(I)
  160 BB(3,1)=BB(3,1)+DB7
      DB8=B(I,3,2)*H(I)
      BB(3,2)=BB(3,2)+DB8
      DB9=B(I,3,3)*H(I)
      BB(3,3)=BB(3,3)+DB9
  200 CONTINUE
      WRITE(6,760) BB(1,1),BB(1,2),BB(1,3),BB(2,1),BB(2,2),BB(2,3),BB(3,
     11),BB(3,2),BB(3,3)
  760 FORMAT(1H1,30X,26HELEMENTS OF B BAR MATRIX  ///(17X,E17.8,5X,E17.8
     1,5X,E17.8))
C CALCULATE ELEMENTS OF C MATRIX
      CX=0.
      DO 300 I=1,N
      DCX=(AX(I)*B(I,1,1)+AY(I)*B(I,1,2)+AXY(I)*B(I,1,3))*H(I)
      CX=CX+DCX
  300 CONTINUE
      CY=0.
      DO 400 I=1,N
      DCY=(AX(I)*B(I,2,1)+AY(I)*B(I,2,2)+AXY(I)*B(I,2,3))*H(I)
      CY=CY+DCY
  400 CONTINUE
      CXY=0.
      DO 500 I=1,N
      DCXY=(AX(I)*B(I,3,1)+AY(I)*B(I,3,2)+AXY(I)*B(I,3,3))*H(I)
      CXY=CXY+DCXY
  500 CONTINUE
C CALCULATE ELEMENTS OF INVERSE OF B-BAR MATRIX
      DBB=BB(1,1)*(BB(2,2)*BB(3,3)-BB(2,3)*BB(3,2))+BB(1,3)*(BB(2,1)*BB(
     13,2)-BB(2,2)*BB(3,1))+BB(1,2)*(BB(3,1)*BB(2,3)-BB(3,3)*BB(2,1))
      BI(1,1)=(BB(2,2)*BB(3,3)-BB(2,3)*BB(3,2))/DBB
  520 BI(1,2)=-(BB(1,2)*BB(3,3)-BB(1,3)*BB(3,2))/DBB
      BI(1,3)=(BB(1,2)*BB(2,3)-BB(1,3)*BB(2,2))/DBB
      BI(2,1)=-(BB(2,1)*BB(3,3)-BB(2,3)*BB(3,1))/DBB
      BI(2,2)=(BB(1,1)*BB(3,3)-BB(1,3)*BB(3,1))/DBB
```

```
540 BI(2,3)=-(BB(1,1)*BB(2,3)-BB(1,3)*BB(2,1))/DBB
    BI(3,1)=(BB(2,1)*BB(3,2)-BB(2,2)*BB(3,1))/DBB
    BI(3,2)=-(BB(1,1)*BB(3,2)-BB(1,2)*BB(3,1))/DBB
560 BI(3,3)=(BB(1,1)*BB(2,2)-BB(1,2)*BB(2,1))/DBB
C CALCULATE ELEMENTS OF ALPHA-BAR MATRIX
    AXB=BI(1,1)*CX+BI(1,2)*CY+BI(1,3)*CXY
    AYB=BI(2,1)*CX+BI(2,2)*CY+BI(2,3)*CXY
580 AXYB=BI(3,1)*CX+BI(3,2)*CY+BI(3,3)*CXY
    WRITE(6,780)AXB,AYB,AXYB
780 FORMAT(1H0,30X,28HELEMENTS OF ALPHA BAR MATRIX//22X,11HALPHA BAR X
   1,11X,11HALPHA BAR Y,11X,12HALPHA BAR XY//(17X,E17.8,5X,E17.8,5X,E1
   27.8))
C CALCULATE STRAINS DEVELOPED IN LAMINATE DUE TO UNIFORM TEMPERATURE
C     INCREASE DT
    EPX=DT*AXB
    EPY=DT*AYB
    EPXY=DT*AXYB
C CALCULATE STRESSES IN EACH PLY
    DO 600 I=1,N
    SX(I)=B(I,1,1)*(EPX-DT*AX(I))+B(I,1,2)*(EPY-DT*AY(I))+B(I,1,3)*
   1(EPXY-DT*AXY(I))
    SY(I)=B(I,2,1)*(EPX-DT*AX(I))+B(I,2,2)*(EPY-DT*AY(I))+B(I,2,3)*
   1(EPXY-DT*AXY(I))
    SXY(I)=B(I,3,1)*(EPX-DT*AX(I))+B(I,3,2)*(EPY-DT*AY(I))+B(I,3,3)*
   1(EPXY-DT*AXY(I))
    A(I,1,1)=T(I,1,1)*D(I,1,1)+T(I,1,2)*D(I,2,1)+T(I,1,3)*D(I,1,3)
    A(I,1,2)=T(I,1,1)*D(I,1,2)+T(I,1,2)*D(I,2,2)+T(I,1,3)*D(I,2,3)
    A(I,1,3)=T(I,1,1)*D(I,3,1)+T(I,1,2)*D(I,3,2)+T(I,1,3)*D(I,3,3)
    A(I,2,1)=T(I,2,1)*D(I,1,1)+T(I,2,2)*D(I,2,1)+T(I,2,3)*D(I,1,3)
    A(I,2,2)=T(I,2,1)*D(I,1,2)+T(I,2,2)*D(I,2,2)+T(I,2,3)*D(I,2,3)
    A(I,2,3)=T(I,2,1)*D(I,3,1)+T(I,2,2)*D(I,3,2)+T(I,2,3)*D(I,3,3)
    A(I,3,1)=T(I,3,1)*D(I,1,1)+T(I,3,2)*D(I,2,1)+T(I,3,3)*D(I,1,3)
     A(I,3,2)=T(I,3,1)*D(I,1,2)+T(I,3,2)*D(I,2,2)+T(I,3,3)*D(I,2,3)
    A(I,3,3)=T(I,3,1)*D(I,3,1)+T(I,3,2)*D(I,3,2)+T(I,3,3)*D(I,3,3)
    SL(I)=A(I,1,1)*EPX+A(I,1,2)*EPY+A(I,1,3)*EPXY-(T(I,1,1)*AL(I)+T(I,
   11,2)*AT(I))*DT
    ST(I)=A(I,2,1)*EPX+A(I,2,2)*EPY+A(I,2,3)*EPXY-(T(I,2,1)*AL(I)+T(I,
   12,2)*AT(I))*DT
    SLT(I)=A(I,3,1)*EPX+A(I,3,2)*EPY+A(I,3,3)*EPXY-(T(I,3,1)*AL(I)+T(I
   1,3,2)*AT(I))*DT
600 CONTINUE
    WRITE(6,800)(I,SX(I),SY(I),SXY(I),I=1,N)
800 FORMAT(1H0,30X,16HTHERMAL STRESSES//8X, 7HPLY NO., 8X,7HALPHA X,15
   1X,7HALPHA Y,15X,8HALPHA XY//(10X,I2,5X,E17.8,5X,E17.8,5X,E17.8))
    WRITE(6,900)(I,SL(I),ST(I),SLT(I),I=1,N)
900 FORMAT(1H0,30X,29HTHERMAL STRESSES NATURAL AXES//8X,7HPLY NO., 8X,
   17HALPHA L,15X,7HALPHA T,15X,8HALPHA LT//(10X,I2,5X,E17.8,5X,E17.8,
   25X,E17.8))
    GO TO 5
    END
       SIZE OF COMMON  00000    PROGRAM  11324
```

Column	NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1		CARD A (2I12,F12.0) 73–80	NM ~ Number of Materials
13			NL ~ Number of Layers
25			DT ~ Temperature Increment in ° F
37			
49			
61			
1		CARD (s) B (5F12.0,2F6.0) 73–80	EL ~ Lamina Longitudinal Young's Modulus
13			ET ~ Lamina Transverse Young's Modulus
25			GLT ~ Lamina Shear Modulus
37			ALPHAL ~ Lamina Long. Coef. of Thermal Expansion
49			ALPHAT ~ Lamina Trans. Coef. of Thermal Expansion
61			ULT ~ Lamina Poisson's Ratio, LT T ~ Lamina Thickness
1		CARD (s) C (6(I6,F6.0)) 73–80	M (1) θ (1) M (I) Material Number of The i^{th} Layer
13			M (2) θ (2)
25			ETC. θ (I) THETA of The i^{th} Layer
37			
49			
61			
1		73–80	
13			
25			
37			
49			
61			

EXAMPLE PROBLEM

To illustrate the use of AC-40, consider a $(0/\pm 45/0)_S$ laminate at room temperature with a $\Delta T = 10°$. For this case, on card A, there are four plies per set, so NL = 4. M is set to 1 for room temperatures properties, and DT is set to 10.0, since $\Delta T = 10°$. The input data sheets and resulting output for this case are shown on the following pages.

The results from the output printout are:

$\bar{\alpha}_x$ = 2.108 μin./in./°F

$\bar{\alpha}_y$ = 5.535 μin./in./°F

$\bar{\alpha}_{xy}$ = 0.0

Ply	σ_x/10°F	σ_y/10°F	σ_{xy}/10°F	σ_L/10°F	σ_T/10°F	σ_{LT}/10°F
1	-93.0	-140.9	0	-93.0	-140.9	0
2	93.0	140.9	294.7	411.6	-177.8	24.0
3	93.0	140.9	-294.7	411.6	-177.8	-24.0
4	-93.0	-140.9	0	-93.0	-140.9	0

NUMBER	IDENTIFICATION	DESCRIPTION DO NOT KEY PUNCH
1		# Materials (NM)
4		# Layers (NL)
10.		ΔT (°F) (DT)
	73 80	
29900000.		E_L
2710000.		E_T
700000.		G_{LT}
.0000232		α_L
.0001067	73 80	α_T
.21 .0052		ν_{LT} t
1 0.		M_1 θ_1
1 45.		M_2 θ_2
1 -45.		M_3 θ_3
1 0.		M_4 θ_4
	73 80	
	73 80	

N-PLY LAMINATE THERMOELASTIC ANALYSIS

N	EL	ET	GLT	ULT	UTL	ALPHAL	ALPHAT	H
1	29900000.	2710000.	700000.	0.2100	0.0190	0.00000232	0.00001067	0.0052

LAYER	N	THETA	LAYER	N	THETA	LAYER	N	THETA	LAYER	N	THETA	LAYER	N	THETA
1	1	0.0	2	1	45.0	3	1	-45.0	4	1	0.0			

ELEMENTS OF D MATRIX

1	0.10000000E 01	0.0	0.0
1	0.0	0.10000000E 01	0.0
1	0.0	0.0	0.10000000E 01
2	0.50000018E 00	0.50000018E 00	-0.99999994E 00
2	0.50000018E 00	0.50000018E 00	0.99999994E 00
2	0.49999994E 00	-0.49999994E 00	0.0
3	0.50000018E 00	0.50000018E 00	0.99999994E 00
3	0.50000018E 00	0.50000018E 00	-0.99999994E 00
3	-0.49999994E 00	0.49999994E 00	0.0
4	0.10000000E 01	0.0	0.0
4	0.0	0.10000000E 01	0.0
4	0.0	0.0	0.10000000E 01

ELEMENTS OF B MATRIX

1	0.30019984E 08	0.57138356E 06	0.0
1	0.57138356E 06	0.27208750E 07	0.0
1	0.0	0.0	0.70000000E 06
2	0.91709110E 07	0.77709080E 07	0.68247770E 07
2	0.77709080E 07	0.91709110E 07	0.68247770E 07
2	0.68247770E 07	0.68247770E 07	0.78995250E 07
3	0.91709110E 07	0.77709080E 07	-0.68247770E 07
3	0.77709080E 07	0.91709110E 07	-0.68247770E 07
3	-0.68247770E 07	-0.68247770E 07	0.78995250E 07
4	0.30019984E 08	0.57138356E 06	0.0
4	0.57138356E 06	0.27208750E 07	0.0
4	0.0	0.0	0.70000000E 06

ELEMENTS OF ALPHA MATRIX

1	0.23199991E-05	0.10670000E-04	0.0

2	0.64350009E-05	0.54950039E-05	-0.83500008E-05
3	0.64950009E-05	0.64950009E-05	0.83500008E-05
4	0.23199991E-05	0.10670000E-04	0.0

ELEMENTS OF H BAR MATRIX

0.40753513E 06	0.86759750E 05	0.0
0.86759750E 05	0.12367444E 06	0.0
0.0	0.0	0.89434938E 05

ELEMENTS OF ALPHA BAR MATRIX

ALPHA BAR X	ALPHA BAR Y	ALPHA BAR XY
0.21081032E-05	0.55350165E-05	0.0

THERMAL STRESSES

PLY NO.	ALPHA X	ALPHA Y	ALPHA XY
1	-0.92951660E 02	-0.14092722E 03	0.0
2	0.92950928E 02	0.14092798E 03	0.29469775E 03
3	0.92950928E 02	0.14092798E 03	-0.29469775E 03
4	-0.92951660E 02	-0.14092722E 03	0.0

THERMAL STRESSES NATURAL AXES

PLY NO.	ALPHA L	ALPHA T	ALPHA LT
1	-0.92951904E 02	-0.14092703E 03	0.0
2	0.41163770E 03	-0.17775775E 03	0.23988373E 02
3	0.41163770E 03	-0.17775775E 03	-0.23988373E 02
4	-0.92951904E 02	-0.14092703E 03	0.0

THERMAL EXPANSION - MACROMECHANICS

Once the elastic and thermal response characteristics for each ply have been determined, the thermal response for an N-ply laminate can be predicted with the use of micromechanics. In this subsection we consider that the ply coefficients of thermal expansion α_L, α_T, α_{LT} are known from testing or the previous micromechanics subsection.

The thermoelastic stress-strain relationship for the i^{th} ply of the laminate for a state of plane-stress, i.e., the stress components normal to the LT plane are taken to be zero, is given as:

$$\begin{Bmatrix} \sigma_L \\ \sigma_T \\ \sigma_{LT} \end{Bmatrix}_i = \begin{bmatrix} T_{11} & T_{12} & 0 \\ T_{12} & T_{22} & 0 \\ 0 & 0 & T_{33} \end{bmatrix}_i \begin{Bmatrix} \epsilon_L - \alpha_L \Delta T \\ \epsilon_T - \alpha_T \Delta T \\ \gamma_{LT} \end{Bmatrix}_i \qquad (28)$$

where:

$$T_{11} = E_L\Big/\left(1 - \nu_{LT}\nu_{TL}\right) = T_{22}\, E_T\big/E_L$$

$$T_{12} = \nu_{TL}\, T_{11} = \nu_{LT}\, T_{22}$$

$$T_{33} = G_{LT}$$

$$\gamma_{LT} = 2\epsilon_{LT}$$

With the use of appropriate coordinate transformations and the foregoing relations, the coefficients of thermal expansion for the N-ply laminate shown in figure 106 are shown in reference 13 to be:

$$\left\{\alpha^c\right\} = \begin{Bmatrix} \alpha_x^c \\ \alpha_y^c \\ \alpha_{xy}^c \end{Bmatrix} = [\bar{B}]^{-1}\left\{C\right\} \tag{29}$$

where the terms on the right side of equation 29 are defined in reference 13, and $\{\alpha^c\}$ are the coefficients of thermal expansion for the laminate. The coefficient α_{xy}^c is associated with a shear mode of thermal distortion and takes on the value of zero whenever the laminate is balanced in the sense that it is composed only of sets of $\pm\theta$ plies. The general picture of thermal distortion of an N-ply laminate due to a uniform temperature change of ΔT is also shown in figure 106.

The equations developed in reference 13 for multi-ply laminates were programed for an IBM 360 computer for application to boron/epoxy laminates. The computer program, designated as AC-40, requires a nominal number of input data for each case and is described in full in reference 13.

CURVES FOR COEFFICIENTS OF THERMAL EXPANSION

In order to assist the designer in predicting the coefficients of thermal expansion for laminates, i.e., α_x^c, α_y^c, α_{xy}^c, curves are presented for laminates of the type $[0_{n1}/\pm 45_{n2}/90_{n3}]_C$, where the designer only needs to know the relative percentages of the plies at 0°, ±45°, and 90°,

where n_1 = number of plies at 0°
$2n_2$ = number of plies at ±45°
n_3 = number of plies at 90°

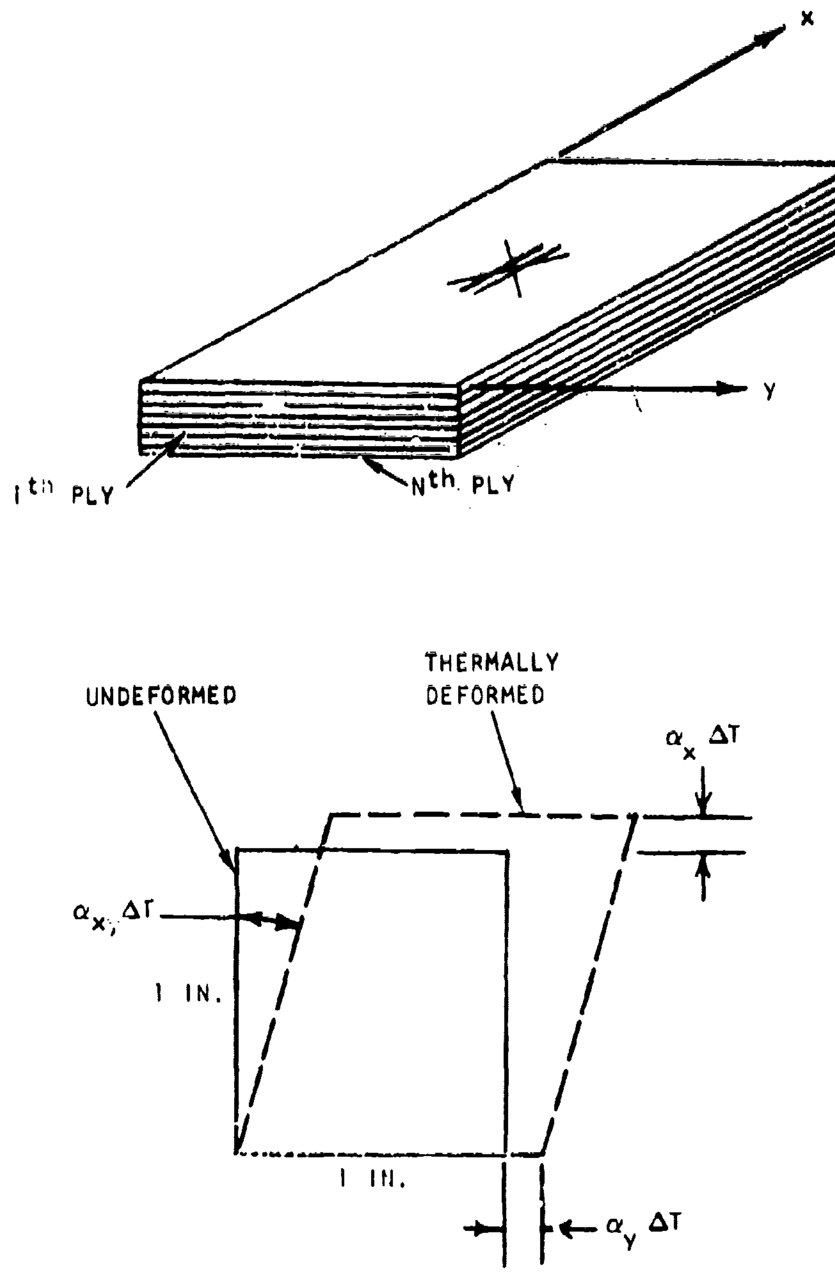


Figure 106. Typical n-Ply Laminate and Thermal Distortion

The RT curve is presented as figure 107a and is for finding α_x^c. If α_y^c is desired, it can be found by reading the curve for α_x^c after interchanging the "% at 0°" and "% at 90°" labels. Further, for this type of laminate, $\alpha_{xy}^c = 0$. Similarly, curves for other laminate families can be developed with the utilization of AC-40. The 350°F curve is presented as figure 107b.

CORRELATION WITH EXISTING ANGLEPLY DATA

Some coefficient of thermal expansion data for $[0_2/\pm45]_C$ and $[0/\pm60]_C$ laminates are available from reference 12 and are compared to values predicted by AC-40. The results of this comparison, shown in table LXXXII indicate that the prediction technique developed on the previous pages is valid at room temperature. However, caution should be used at elevated temperatures because of the nonlinearity of the unidirectional transverse α_T.

TABLE LXXXII. COMPARISON OF PREDICTED VALUES AND TEST DATA FOR COEFFICIENTS OF THERMAL EXPANSION AT ROOM TEMPERATURE

$[0_2/\pm45]_C$				$[0/\pm60]_C$			
α_x^c μ in./in./°F		α_y^c μ in./in./°F		α_x^c μ in./in./°F		α_y^c μ in./in./°F	
Pred	Test	Pred	Test	Pred	Test	Pred	Test
2.11	2.60	5.54	6.10	3.13	3.25	3.13	3.3

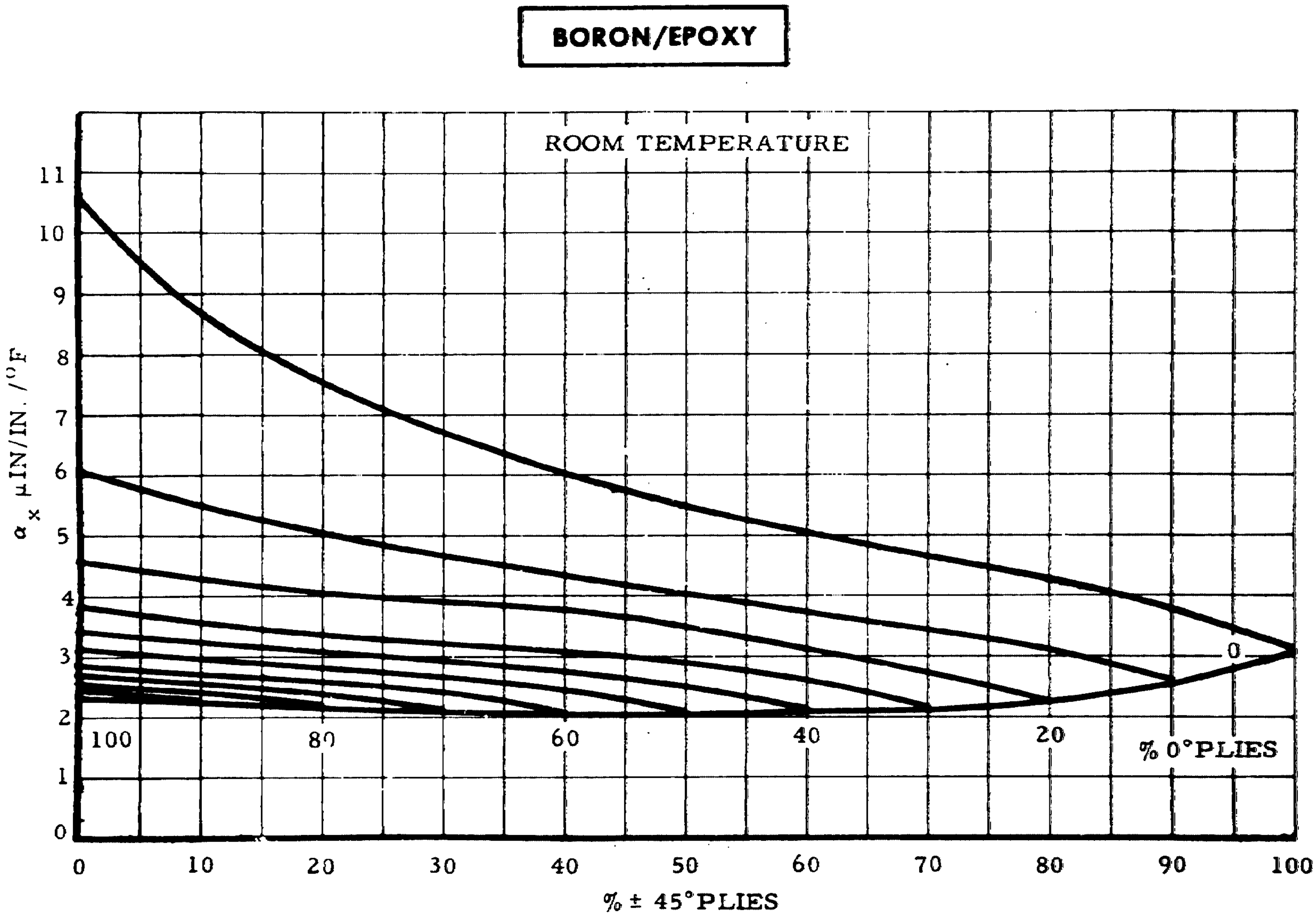


Figure 107a. Longitudinal Coefficient of Thermal Expansion for Laminates of Type $[0_{n_1} / \pm 45_{n_2} / 90_{n_3}]_C$ at Room Temperature

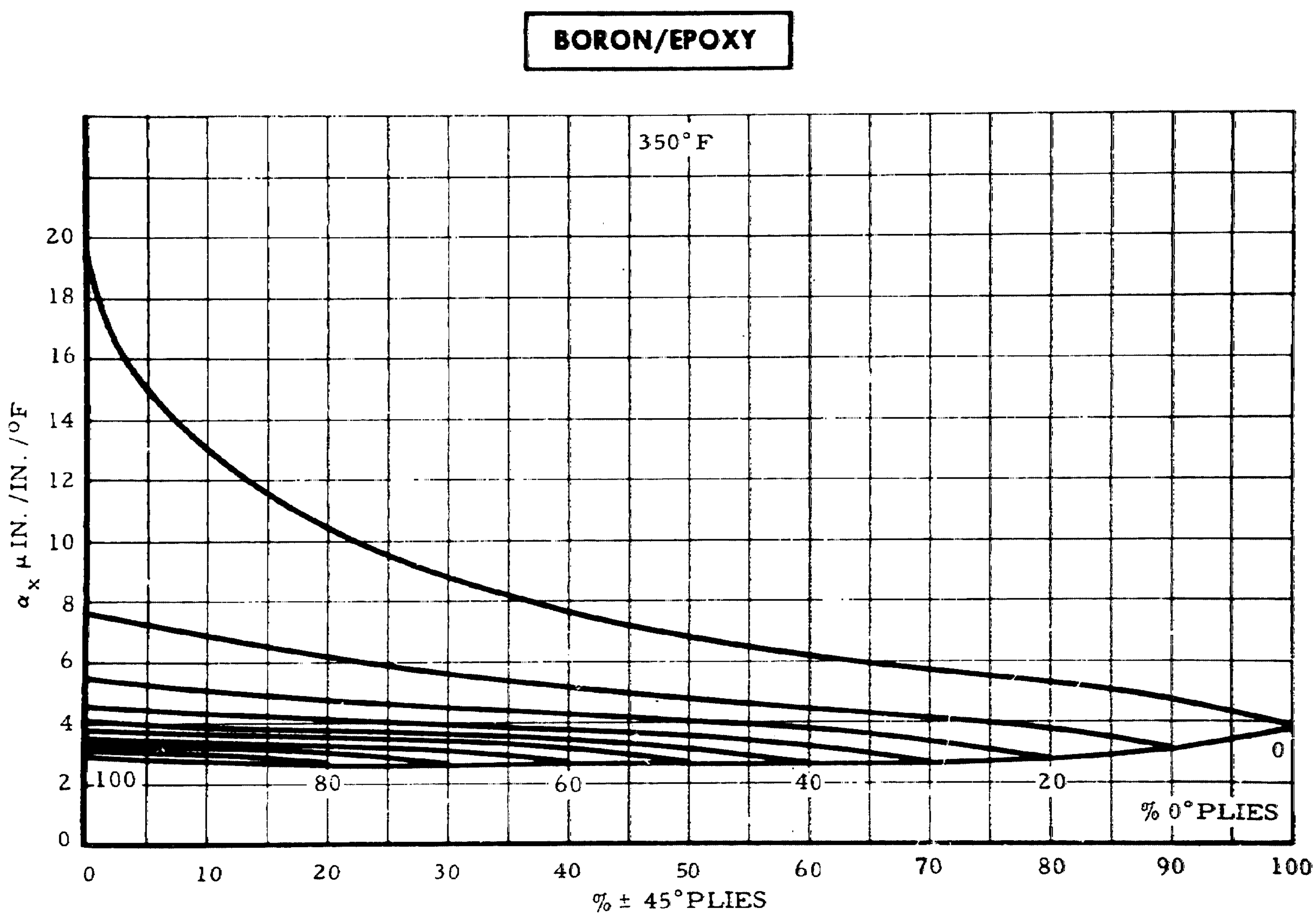


Figure 107b. Longitudinal Coefficient of Thermal Expansion for Laminates of Type $[0_{n_1} / \pm 45_{n_2} / 90_{n_3}]_C$ at 350°F.

D_{ij}'s OF SOME COMMONLY USED LAMINATES

Let us now consider symmetric laminates composed of q sets of plies with each set having p_1 plies at 0°, $2p_\theta$ plies at ±θ°, and p_2 plies at 90° as shown in figure 5.

Let

$$\phi(i) = 3\left(i - \frac{N+1}{2}\right)^2 + \frac{1}{4} \tag{15}$$

and

$$r = p_1 + 2p_\theta + p_2$$

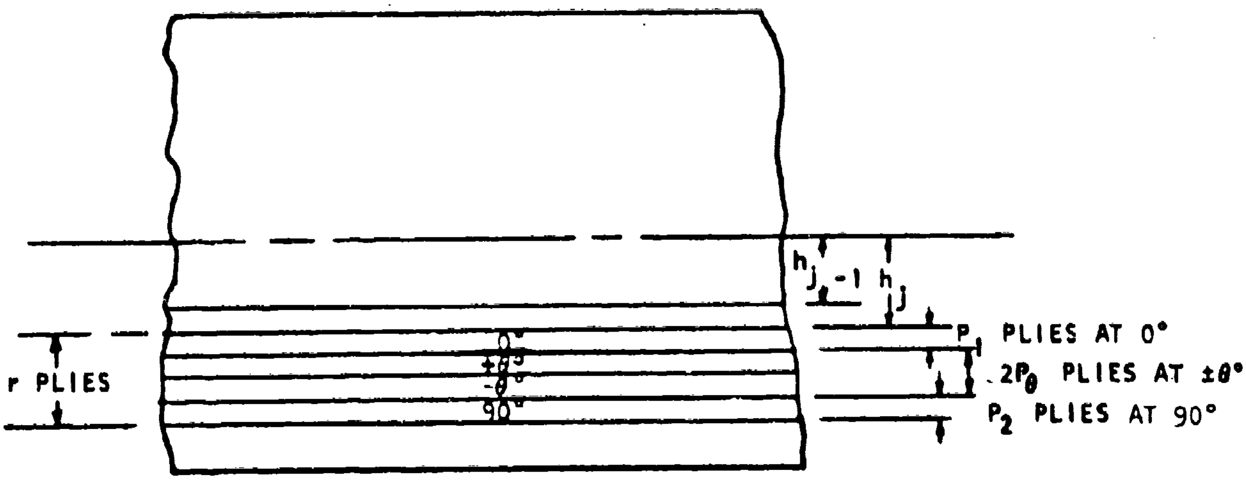


Figure 5. Typical Symmetrical Laminate

then

$$D_{11} = \frac{2}{3} h^3 \sum_{k=1}^{q/2} \left\{ \left(\bar{Q}_{11}\right)_{0^\circ} \sum_{i=\left(\frac{N}{2}+1\right)+(k-1)r}^{\left(\frac{N}{2}+1\right)+(k-1)r+p_1-1} \phi(i) \right.$$

$$+ \left(\bar{Q}_{11}\right)_{\theta^\circ} \sum_{i=\left(\frac{N}{2}+1\right)+(k-1)r+p_1}^{\left(\frac{N}{2}+1\right)+(k-1)r+p_1+2p_\theta-1} \phi(i)$$

$$\left. + \left(\bar{Q}_{11}\right)_{90^\circ} \sum_{i=\left(\frac{N}{2}+1\right)+(k-1)r+p_1+2p_\theta}^{\left(\frac{N}{2}+1\right)+kr-1} \phi(i) \right\}$$

$$D_{11} = \frac{2}{3} h^3 \sum_{k=1}^{q/2} \left\{ \left(\bar{Q}_{11}\right)_{0^\circ} \sum_{j=1}^{p_1} \phi\left[\frac{N}{2}+j+(k-1)r\right] \right.$$

$$+ \left(\bar{Q}_{11}\right)_{\theta^\circ} \sum_{j=1}^{2p_\theta} \phi\left[\frac{N}{2}+j+(k-1)r+p_1\right]$$

$$\left. + \left(\bar{Q}_{11}\right)_{90^\circ} \sum_{j=1}^{p_2} \phi\left[\frac{N}{2}+j+(k-1)r+p_1+2p_\theta\right] \right\} \tag{16}$$

$$= \frac{2}{3} h^3 \sum_{k=1}^{q/2} \left\{ \left(\bar{Q}_{11}\right)_{0^\circ} \sum_{j=1}^{p_1} \phi\left(j+kr+r_1\right) \right.$$

$$\left. + \left(\bar{Q}_{11}\right)_{\theta^\circ} \sum_{j=1}^{p_{2_\theta}} \phi\left(j+kr+r_2\right) + \left(\bar{Q}_{11}\right)_{90^\circ} \sum_{j=1}^{p_2} \phi\left(j+kr+r_3\right) \right\}$$

where

$$r_1 = \frac{N}{2} - r$$

$$r_2 = \frac{N}{2} - 2p_\theta - p_2 \qquad (17)$$

$$r_3 = \frac{N}{2} - p_2$$

Letting

$$C_A = \sum_{k=1}^{q/2} \sum_{j=1}^{p_1} \phi\,(j + kr + r_1)$$

$$C_B = \sum_{k=1}^{q/2} \sum_{j=1}^{2p_\theta} \phi\,(j + kr + r_2) \qquad (18)$$

$$C_C = \sum_{k=1}^{q/2} \sum_{j=1}^{p_2} \phi\,(j + kr + r_3)$$

then

$$D_{11} = \frac{2}{3} h^3 \left[C_A \,(\bar{Q}_{11})_0 + C_B \,(\bar{Q}_{11})_\theta + C_C \,(\bar{Q}_{11})_{90} \right] \qquad (19)$$

Expanding ϕ in equation 18 and noting that

$$\sum_{n=1}^{N} n^2 = \frac{N}{6} (N+1) \; (2N+1)$$

$$\qquad (20)$$

$$\sum_{n=1}^{N} n = \frac{N}{2} (N+1)$$

$$C_A = \frac{q\,p_1}{4}\left|(p_1+1)\left[2p_1 + 1 + 3\,(2r_1 - N - 1)\right] + \frac{3}{2}\,(2r_1 - N - 1)^2 + \frac{1}{2}\right|$$

$$+ 3rp_1\,(p_1 + 2r_1 - N)\,\frac{q}{2}\,\frac{\left(\frac{q}{2}+1\right)}{2} + 3p_1\,r^2\,\frac{q}{2}\,\frac{\left(\frac{q}{2}+1\right)\left(q+1\right)}{6}$$

$$= \frac{q\,p_1}{8}\left[2(p_1+1)\,(2p_1 + 6r_1 - 3N - 2) + 3\,(2r_1 - N - 1)^2 + r\,(q+2)\,(3p_1 + 6r_1 - 3N + r + qr) + 1\right] \qquad (21)$$

By replacing r_1 by r_2 and p_1 by $2p_\theta$ in the preceding equation, we obtain

$$C_B = \frac{qp_\theta}{4}\left[2(2p_\theta+1)\,(4p_\theta+6r_2-3N-2) + 3(2r_2-N-1)^2 + r(q+2)\,(6p_\theta+6r_2-3N+r+qr) + 1\right] \qquad (22)$$

By replacing r_1 by r_3 and p_1 by p_2 in equation 21, we obtain

$$C_C = \frac{qp_2}{8}\left[2(p_2+1)\,(2p_2+6r_3-3N-2) + 3(2r_3-N-1)^2 + r(q+2)\,(3p_2+6r_3-3N+r+qr) + 1\right] \qquad (23)$$

The preceding results are also applicable to D_{12}, D_{22}, and D_{66}. The resulting expressions are

$$(D_{11}, D_{12}, D_{22}, D_{66}) = \frac{2}{3}\,h^3\left\{\left[(\bar{Q}_{11})_0, (\bar{Q}_{12})_0, (\bar{Q}_{22})_0, (\bar{Q}_{66})_0\right]C_A + \left[(\bar{Q}_{11})_\theta, (\bar{Q}_{12})_\theta, (\bar{Q}_{22})_\theta, (\bar{Q}_{66})_\theta\right]C_B + \left[(\bar{Q}_{11})_{90}, (\bar{Q}_{12})_{90}, (\bar{Q}_{22})_{90}, (\bar{Q}_{66})_{90}\right]C_C\right| \qquad (24a)$$

where it should be noted that the $(\bar{Q}_{ij})$'s are evaluated for $+\theta°$. In order to evaluate D_{16} and D_{26}, the existence of both $\pm\theta$ plies must be considered. By following a similar procedure, we get

$$(D_{16}, D_{26}) = 2/3h^3 \, [(\bar{Q}_{16})_\theta \, , \, (\bar{Q}_{26})_\theta \,] \, C'_B \tag{24b}$$

where

$$C'_B = 3qp_\theta \, [-p_\theta + \frac{N}{2} - r_2 - \frac{r}{4}(q + 2)]$$

Equations (24) represent the closed-form sums for the flexural stiffnesses of a laminate composed of q repeated sets of $[0_{p_1}/\pm\theta_{p_\theta}/90_{p_2}]$ laid up symmetrically relative to the midsurface of the laminate. These stiffnesses are required to conduct analyses of orthotropic laminated plates. The equivalent extensional constants are obtained by combining equations 13 and 14 in the appropriate manner.

For cases when a more general laminate layup is under consideration, equation 9, which is valid for any laminate ply orientations, should be utilized.

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13. ABSTRACT

This volume summarizes that portion of the program concerned with the material and basic allowable development of a current graphite/epoxy advanced composite system. The specific system characterized is known commercialy as Type AS/3002 prepregged by Fiberite Corp, with the fiber and matrix formulation supplied by Hercules Inc, the U.S. licensed distributor of Courtauld's fibers. The test program was divided into two categories: "baseline" data and "environmental effects" data. The baseline data provided the standard mechanical properties, bonded and mechan. l joint data, and fundamental configuration data at room, elevated (350°F), and subzero (-65°F) temperature to support the basic design of graphite/epoxy airframe structural components. Both static and fatigue data are presented. These data were augmented by the environmental effects data, which established the influence of the operating environment of high-performance aircraft on the design allowables of the graphite/epoxy system studied. Basic design allowables for both unidirectional and the general family of $[0_i/\pm45_j/90_k]$ crossplied laminates are presented.

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Strength Properties of Composites						
Elastic Constants of Composites						
Thermal-Physical Constants of Composites						
Fatigue Testing						
Environmental Testing						
Adhesives						
Bonded Joints						
Mechanically Fastened Joints						